

DEPARTMENT OF COMPUTER SCIENCE
SERIES OF PUBLICATIONS A
REPORT A-2017-2

Exploring Hand-Based Haptic Interfaces for Mobile Interaction Design

Yi-Ta Hsieh

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public examination in Auditorium CK112, Exactum, University of Helsinki, on June 8th, 2017, at 12 o'clock noon.

UNIVERSITY OF HELSINKI
FINLAND

Supervisors

Giulio Jacucci, University of Helsinki, Finland
Eve Hoggan, Aarhus University, Denmark

Pre-examiners

Charlotte Magnusson, Lunds University, Sweden
Enrico Rukzio, Ulm University, Germany

Opponent

Kaisa Väänänen, Tampere University of Technology, Finland

Custos

Giulio Jacucci, University of Helsinki, Finland

Contact information

Department of Computer Science
P.O. Box 68 (Gustaf Hällströmin katu 2b)
FI-00014 University of Helsinki
Finland

Email address: info@cs.helsinki.fi
URL: <http://www.cs.helsinki.fi/>
Telephone: +358 2941 911, telefax: +358 9 876 4314

Copyright © 2017 Yi-Ta Hsieh
ISSN 1238-8645
ISBN 978-951-51-3463-9 (paperback)
ISBN 978-951-51-3464-6 (PDF)
Computing Reviews (1998) Classification: H.5.1, H.5.2
Helsinki 2017
Unigrafia

Exploring Hand-Based Haptic Interfaces for Mobile Interaction Design

Yi-Ta Hsieh

Department of Computer Science
P.O. Box 68, FI-00014 University of Helsinki, Finland
yi-ta.hsieh@helsinki.fi

PhD Thesis, Series of Publications A, Report A-2017-2
Helsinki, June 2017, 79+120 pages
ISSN 1238-8645
ISBN 978-951-51-3463-9 (paperback)
ISBN 978-951-51-3464-6 (PDF)

Abstract

Visual attention is crucial in mobile environments, not only for staying aware of dynamic situations, but also for safety reasons. However, current mobile interaction design forces the user to focus on the visual interface of the handheld device, thus limiting the user's ability to process visual information from their environment. In response to these issues, a common solution is to encode information with on-device vibrotactile feedback. However, the vibration is transitory and is often difficult to perceive when mobile. Another approach is to make visual interfaces even more dominant with smart glasses, which enable head-up interaction on their see-through interface. Yet, their input methods raise many concerns regarding social acceptability, preventing them from being widely adopted. There is a need to derive feasible interaction techniques for mobile use while maintaining the user's situational awareness, and this thesis argues that solutions could be derived through the exploration of hand-based haptic interfaces.

The objective of this research is to provide multimodal interaction for users to better interact with information while maintaining proper attention to the environment in mobile scenarios. Three research areas were identified. The first is developing expressive haptic stimuli, in which the research investigates how static haptic stimuli could be derived. The second is designing mobile spatial interaction with the user's surroundings as content, which manifests situations in which visual attention to the environment is most needed. The last is interacting with the always-on visual interface

on smart glasses, the seemingly ideal solution for mobile applications. The three areas extend along the axis of the demand of visual attention on the interface, from non-visual to always-on visual interfaces.

Interactive prototypes were constructed and deployed in studies for each research area, including two shape-changing mechanisms feasible for augmenting mobile devices and a spatial-sensing haptic glove featuring mid-air hand-gestural interaction with haptic support. The findings across the three research areas highlight the immediate benefits of incorporating hand-based haptic interfaces into applications. First, shape-changing interfaces can provide static and continuous haptic stimuli for mobile communication. Secondly, enabling direct interaction with real-world landmarks through a haptic glove and leaving visual attention on the surroundings could result in a higher level of immersed experience. Lastly, the users of smart glasses can benefit from the unobtrusive hand-gestural interaction enabled by the isolated tracking technique of a haptic glove.

Overall, this work calls for mobile interaction design to consider haptic stimuli beyond on-device vibration, and mobile hardware solutions beyond the handheld form factor. It also invites designers to consider how to confront the competition of cognitive resources among multiple tasks from an interaction design perspective.

Computing Reviews (1998) Categories and Subject Descriptors:

- H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities
- H.5.2 [Information Interfaces and Presentation]: User Interfaces— Haptic I/O, Input devices and strategies

General Terms:

Design and Experimentation

Additional Key Words and Phrases:

Mobile Spatial Interaction, Interaction Design, Interaction Techniques, Shape-Changing Interface, Mid-Air Hand-Gestural Interaction, Head-Mounted Display

Acknowledgements

Firstly, I am grateful to my supervisor, Professor Giulio Jacucci. He gave me the opportunity to conduct the research with the greatest support with academic resources as well as the flexibility for me to work from my home country when my family needed me. His persisting purposeful guidance has enabled me to explore the research area while remaining focused. I also thank Giulio for bringing me to the CultAR project and Flint project which not only financially supported my research but also gave me a great chance to work with a bunch of exceptional people.

I also want to thank Associate Professor Eve Hoggan at Aarhus University for acting as a second supervisor. Without her brilliant input and insightful discussions we had together, the research could not have been properly shaped. I have been fortunate to have Antti Jylhä as my mentor. His input, support, encouragement and guidance have greatly smoothed and deepened my research journey. More importantly, he taught me research practises without reservation.

By no means could this research have been done alone. I am grateful to my colleagues and co-authors of the articles that form elements of the thesis, especially my Italian friends: Professor Luciano Gamerini, Professor Anna Spagnolli, Valeria Orso, Maura Bellio, and Manuela Canaveras. The seamless cooperation between the Helsinki and Padova groups has been the key to the research achievements. I also want to thank Konrad Markus and Walther Jensen for the unique experience in prototyping research tools together. In addition to the previously mentioned ones, I wish to thank the members of Ubiquitous Interaction research group who have not only contributed to the work in various ways but also accompanied the journey as sincere friends: Salvatore Andolina, Diogo Cabral, Imtiaj Ahmed, Oswald Barral, Khalil Klouche, Baris Serim, Zachary Laster, Ilkka Kosunen, Matti Nelimarkka, Kalle Myllymaa, Jukka Leino, Antti Salovaara, Tuukka Ruotsalo, Joanna Bergström-Lehtovirta, Kumaripaba Athukorala, Antti Nurminen, Luana Micallef, Andrea Vianello, and Julian Eiler. Many thanks to Vuokko Lantz, Johan Kildal, and Teemu Tuomas Ahmaniem at

Nokia Research Center who gave me the opportunity to experience research from an industrial perspective.

My family has been the strongest pillar supporting me in pursuing my goals. I am grateful to my parents and my sisters who are always ready to support me in any form through out my life. Special thanks go to my wife Wen for her tremendous love, patience, sacrifice and tolerance. Living apart can never be easy for any couple, yet she is so special that made this meaningful.

Taipei, May 6th, 2017
Yi-Ta Hsieh

Contents

1	Introduction	1
1.1	Design Space: From Non-Visual to Always-On Visual Interfaces	6
1.1.1	Developing Expressive Haptic Stimuli	7
1.1.2	Designing Mobile Spatial Interaction with Surroundings as Content	7
1.1.3	Interacting with Always-On Visual Interface	8
1.1.4	Summary of the Design Space	9
1.2	Research Questions	11
1.2.1	Claims	12
1.3	Structure of the Thesis	14
2	Background	15
2.1	Attention and Visual Dominance	15
2.2	Haptic Stimuli Beyond On-Device Vibrotactile Feedback . .	16
2.3	MSI Hardware Solutions Beyond the Handheld Form Factor	18
2.4	Do Smart Glasses Solve the Problems?	21
2.5	Summary	23
3	Research Methods	25
3.1	Research Strategy in Area I	26
3.2	Research Strategy in Area II	26
3.3	Research Strategy in Area III	28
4	Messaging with Textures on Shape-Changing Interfaces	31
4.1	Design of the System	32
4.2	The Studies	32
4.3	Findings and Claims	34

5	Hand-Gestural Interaction in MSI Applications	37
5.1	Design of the Hand-Worn System	38
5.2	The Studies	41
5.2.1	Study 1 - Tactile Cue Design Considering Natural Pointing Gestures	42
5.2.2	Study 2 - Target Acquisition in Urban Environment	45
5.2.3	Study 3 - Urban Exploration through Audio-Haptic Interface	46
5.2.4	Study 4 - Complementing Audio-Haptic Urban Ex- plorer with Augmented Reality	49
5.3	Findings and Claims	50
6	Hand-Gestural Interaction with Smart Glasses	53
6.1	Design of the System	53
6.2	The Study	54
6.3	Findings and Claims	56
7	Conclusion	59
7.1	Summary of the Main Findings	59
7.2	Implications of the Research	62
7.3	Limitations	63
7.4	Future Research	64
	References	67
	Original articles	81

List of Publications

This thesis consists of an overview and the following six publications, referred to as Publications I-VI. The following authors have contributed to these publications, and my contributions to them are detailed as follows. The publications are reprinted at the end of the thesis.

Publication I: Eve Hoggan, Yi-Ta Hsieh, Kalle Myllymaa, Vuokko Lantz, Johan Kildal, Julian Eiler, and Giulio Jacucci. 2017. An Exploration of Mobile Shape-Changing Textures. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*. 275-282, ACM Press, 2017.

Contribution: Together with Eve Hoggan and Kalle Myllymaa, the author explored possible mechanisms for shape-changing interfaces. The author, Kalle Myllymaa, and Julian Eiler designed and prototyped the final concepts of the mechanisms. The user studies were designed by the author and Eve Hoggan, with feedback received from Vuokko Lantz, Johan Kildal, and Giulio Jacucci, while the studies were conducted by the author and Julian Eiler. The analysis and the first draft of the paper were written by Eve Hoggan. All of the authors participated in the revisions.

Publication II: Yi-Ta Hsieh, Antti Jylhä, and Giulio Jacucci. 2014. Pointing and Selecting with Tactile Glove in 3d Environment. In *Proceedings of the Symbiotic Interaction: Third International Workshop, Symbiotic 2014*, 133-137, Springer International Publishing, 2014.

Contribution: This publication describes the design and applications of a glove system that was designed and implemented mainly by the author, who received guidance and feedback from Antti Jylhä and Giulio Jacucci. The author demonstrated the system in the international workshop. The author drafted the first version of the paper. All of the authors participated in revisions.

Publication III¹: Yi-Ta Hsieh, Antti Jylhä, Valeria Orso, Salvatore Andolina, Eve Hoggan, Luciano Gamberini, and Giulio Jacucci. Developing Hand-Worn Input and Haptic Support for Mobile Spatial Interaction.

Contribution: The publication is a summarizing work of the iterative development of a glove system, including three user studies. The systems and prototypes were mainly designed and implemented by the author, who received feedback from all of the other authors. The data in the studies were partly analyzed by the author. The author drafted the first version of the paper. All of the authors participated in the revisions.

Publication IV: Antti Jylhä, Yi-Ta Hsieh, Valeria Orso, Salvatore Andolina, Luciano Gamberini, and Giulio Jacucci. 2015. A Wearable Multimodal Interface for Exploring Urban Points of Interest. In *Proceedings of the 2015 ACM on International Conference on Multimodal Interaction (ICMI '15)*, 175-182, ACM Press, 2015.

Contribution: The system and the interaction were mainly designed and implemented by the author, who received feedback from all of the other authors. The author designed the study together with Antti Jylhä, Valeria Orso, and Salvatore Andolina, with feedback received from Luciano Gamberini and Giulio Jacucci. The study was conducted by Valeria Orso. The author contributed part of the data analysis. Antti Jylhä was the lead author of this paper. All of the authors participated in revisions.

Publication V²: Yi-Ta Hsieh, Valeria Orso, Manuela Canaveras, Diogo Cabral, Salvatore Andolina, Anna Spagnoli, Luciano Gamberini, and Giulio Jacucci. 2017. Interweaving Augmented Reality and Audio-Haptic Interfaces for Cultural Heritage Exploration in Urban Environment.

Contribution: The author designed the system and the interaction, and received feedback from all of the other authors. The author implemented the system based on the system platform of the CultAR project. The author designed the study together with Valeria Orso, Diogo Cabral, and Salvatore Andolina, while Anna Spagnoli, Luciano Gamberini, and Giulio Jacucci provided feedback. Valeria Orso and Manuela Canaveras conducted the study and analyzed most of the data. The author contributed part of the data analysis. The author drafted the first version of the paper. All of the authors participated in the revisions.

¹Submitted to: the *Personal and Ubiquitous Computing* journal

²Submitted to: the *Special Issue on Advanced Interfaces for Cultural Heritage, the International Journal of Human-Computer Studies*

Publication VI: Yi-Ta Hsieh, Antti Jylhä, Valeria Orso, Luciano Gamberini, and Giulio Jacucci. 2016. Designing a Willing-to-Use-in-Public Hand Gestural Interaction Technique for Smart Glasses. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, 4203-4215, ACM Press, 2016.

Contribution: The author designed and implemented both a system and an interaction, while receiving feedback from all of the other authors. The author designed the study together with Antti Jylhä and Valeria Orso, with Luciano Gamberini and Giulio Jacucci providing feedback. The author conducted the study. The author analyzed the data with Valeria Orso. The author drafted the first version of the paper. All of the authors participated in the revisions.

Chapter 1

Introduction

Visual attention is crucial in mobile environments, not only for staying aware of dynamic situations but also for safety reasons [29]. However, mobile technologies on modern smartphones nowadays rely on visual interfaces to deliver information and draw even more of the users' attention onto the devices by providing intriguing content and interactions, leaving limited resources for the surroundings. Or the other way around, concurrent mobile tasks could be interrupted by the need for monitoring the environment. Oulasvirta et al. discovered that continuous attention to the mobile device can be broken down to bursts of 4 to 8 seconds in order to keep aware of the surroundings [71]. The phenomenon of multiple tasks competing for the users' cognitive resources is especially prominent in mobile conditions. As illustrated by Wickens [105], the 4-dimension multiple resource model can be used to explain and predict performance in a multi-task setting. Greater interference can be identified between two tasks if they share one of the following dimensions: processing stages (perception, cognition, and responding), perceptual modalities (visual vs. auditory), processing codes (verbal vs. spatial), and visual channels (focal vs. ambient) (see Figure 1.1). Although focal and ambient vision seem to function well in parallel (e.g., reading a book while walking down a corridor) in the dimension of visual channels, it becomes a matter of sharing time between two tasks on the dimension of sensory modalities when more attention is required on the surroundings (e.g., matching current location on a map by searching visual cues from the environment). This kind of time sharing between sensory modalities is found to be poorer in intra-modal tasks (visual-visual) than in cross-modal tasks (auditory-visual) [105]. While rich content can be delivered through fast-responding touchscreens on handheld devices, much cognitive resources are needed on or drawn to the visual interface, requiring users to split their attention between the device and their surroundings,

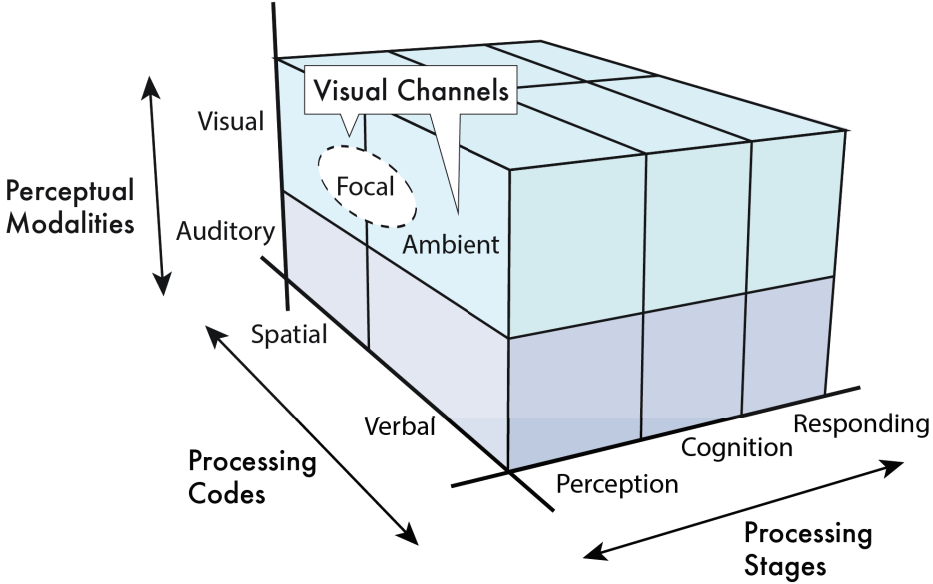


Figure 1.1: The schematic representation of the 4-dimensional multiple resource model. The dimension of Visual Channels is nested within visual resources (adapted from [105]).

hampering the user experience or resulting in users ignoring their surroundings.

To be more specific, two major problems have been largely discussed in mobile contexts. Firstly, it is **difficult to interact with information while users are on the move**. Not only does visual attention on interfaces constrain free body movement [26], but mobile users also often struggle with manipulating multiple physical objects simultaneously [61, 70, 94]. Ng et al. found that input accuracy can decrease by almost 50% when walking and carrying objects in the other hand [67]. Karlson et al. also observed that 65% of mobile users had an extra physical object in the other hand while using the phone [45]. Although the compact size of handheld devices allows them to be carried conveniently within a pocket or a handbag, and rudimentary tactile or audio feedback is provided for alerting notifications, users still need to take their phone from their pocket for direct visual contact with the screen to access the information. If an instant response to information is required, users need to hold the device in their hand and maintain constant visual attention to it, or break down the concurrent tasks into segments [71]. In mobile conditions, the accessibility of the information in both situations (in the pocket or in the hand) down-

grades severely, and the performance is largely confined by the handheld form factor, related physical constraints [70], and walking speed [7].

Another issue is the phenomenon that people fail to notice new and distinctive stimuli in the surroundings, which is known as **inattentional blindness** [5, 56, 90]. This is due to the division of people’s attention and is more likely to happen when executive working memory, not just information maintenance, is involved in the task [22]. Moreover, increasing the demand of attention on the task can increase the chances of inattentional blindness [90]. As mobile applications provide more and more intriguing content, interacting with the device demands more cognitive manipulation. The touchscreen-style interaction technique also requires constant visual attention, leaving limited resources for the surroundings. Empirical experiments have already confirmed that people are likely to miss distinctive events taking place in the surroundings while using mobile devices [29, 40]. Even with company, people are often found to be immersed in another world behind the visual interface. Misra et al. investigated the effect of mobile devices on in-person social interaction [66]. They found that the quality of a conversation was rated worse in the presence of mobile device, as compared to the condition without mobile devices.

Inattentional blindness, or ignoring the surroundings, can be a more severe issue when the immediate surroundings also constitute part of the content. For example, in tourism contexts, touchscreen users can be found head down and concentrating on the device, rather than on the environment where the real content is. An indirect example is Henkel’s experiment on the influence of taking pictures during a guided tour in a museum [35]. Participants who took pictures throughout the tour remembered fewer objects, fewer details about the objects, and fewer of the objects’ locations in the museum, compared with those who did not take pictures. The recent, popular location-aware mobile game Pokémon Go¹ states an alert message explicitly on the welcoming page: “Remember to be alert at all times. Stay aware of your surroundings.” This clearly implies users’ tendency to ignore the surroundings when an application requires much attention. The phenomenon is so prominent that the company needs to display this message to avoid any potential legal issues. Even when the user’s attention is divided between the handheld device and the surroundings, the tasks demand the same resources and must be processed sequentially, resulting in poorer performance, according to the multiple resource model [105]. In sum, **the domination of visual interfaces** and the **handheld form factor** in mobile interaction can consume the users’ visual resources.

¹<http://www.pokemon.com/us/pokemon-video-games/pokemon-go/>

Incorporating sensory modalities other than vision into interactions could potentially reserve more visual resources for the environment. Modern smartphones have already deployed haptic stimuli, mainly through on-device vibrotactile feedback, so that interactions do not rely solely on vision and can potentially reduce the demand on visual resources. For example, the system can alert the user of push notifications by triggering a vibration on the device, so that constant visual examination of the display can be avoided. More sophisticated applications can be achieved by manipulating the vibrotactile parameters, such as encoding information with tactons [9]. However, this type of interaction is limited and transitory, meaning that the stimuli can only be perceived during their activation period and when in good contact with the skin. Previous research has shown that tactile perception differs depending on the body location [13]. Hence, even if the device is physically in contact with the user, if it is in contact with less sensitive areas of the body, the detection threshold will be higher. Furthermore, movement also significantly affects tactile perception. For example, NaviRadar [85] is a pedestrian navigation technique that utilizes a distinct tactile pattern to communicate the distance to the next waypoint and the direction to turn. No visual attention is required on the interface. However, the guidance cues might easily be missed unless the device is held in hand along the way. Another pedestrian navigator example is PocketNavigator [74]. Even though the device was placed in the pocket during the evaluation of the system, the participants needed to touch their pocket to perceive the vibration properly when on the move. Research has also shown that many users miss alerts from their mobile devices because of these perception issues [46]. Even if the stimuli are successfully perceived, visual examination of the interface is still needed eventually.

Instead of exploiting other modalities in interactions, another approach to ease the competition for visual resources between the interface and the surroundings during the interaction is on the other extreme of the spectrum: to make visual interfaces even more dominant through head-mounted displays with see-through technologies, such as smart glasses. As a type of wearable technology, smart glasses enable hands-free and head-up interaction, which largely increases information accessibility on the move. Moreover, the see-through technology allows users to maintain their awareness of their surroundings. However, concerns regarding social acceptability prevent this technology from gaining more popularity, mainly due to the fact that the input techniques raise too much attention from bystanders [50, 55, 96]. For example, a sudden burst of voice commands can gather significant attention from other people sharing the same space. Even worse, it

could be disturbing. Another example is hand gestures performed on the frame or in front of the eyes. Simply raising one’s hand would already gain much attention from the crowd, not to mention have fatigue issues [96]. Both approaches are commonly available on smart glasses on the market. Unfortunately, they are neither efficient nor pleasant.

Design strategies can be formulated from the above discussion. As described in multiple resource theory, if tasks compete for the same resource, they must be processed sequentially, i.e., through time-sharing [105]. The design of mobile devices concentrates most of our resources on the handheld device and its visual interface, which makes it challenging to multi-task under practical mobile situations. When holding the device in our hand, manipulating other physical objects competes for our motor resources. When interacting with the visual interface, being aware of the surroundings competes for our visual resources. Simply paying attention to the visual interface would already constrain free body movement [26]. Since the multiple resource model also suggests that cross-modal time-sharing (e.g., listening to an audio guide while observing a painting) is better than intra-modal time-sharing (e.g., listening to two distinct conversations) [105], a straightforward approach is to develop a non-visual interface, or a multimodal interface which incorporates multiple sensory modalities. Among all of the sensory modalities other than vision, the haptic modality appears to be the most promising option, since it has manifested many useful and well-established solutions in different contexts. Examples range from emulating sense of touch in virtual environments [11, 24, 28] and for directional guidance and navigation [1, 63, 68, 85] to multimodal applications incorporating both audio and haptic modalities [60, 97, 103]. Therefore, **exploring hand-based haptic interfaces is the main design approach used in this thesis for deriving practical solutions.**

More specifically, the design approach can be further formulated into two directions: 1) **developing haptic stimuli beyond on-device vibrotactile feedback** and 2) **developing mobile hardware solutions beyond the handheld form factor**. Since the idea is to avoid requiring visual resources for the interface, the delivery of information largely relies on haptic resources. Increasing the expressiveness of the haptic stimuli can effectively benefit users. As mentioned earlier, although conveniently available, on-device vibrotactile stimuli cannot be properly perceived in mobile conditions. New alternatives to haptic stimuli need to be developed. The second direction aims at seeking solutions beyond the handheld form factor. Holding the device in the hand results in tasks competing for our motor resources, as well as constant attention on the device and impaired mobility.

Without having to hold a device in their hand, users can immediately enjoy the benefit of unconstrained mobility, which is essential in mobile interaction. This design approach has led to the prototypes utilized as research tools in this thesis.

The main objective of this research is to **provide multimodal interaction for users to better interact with information while maintaining proper attention to the environment** in practical mobile scenarios. As a result, two design concepts are proposed. One concept is to deploy a shape-changing interface onto mobile devices so that the texture of the device surface could be encoded with information for mobile communication. The other is the Spatial Sensing Haptic Glove (SSH Glove), which affords hand-gestural recognition and tactile feedback for both Mobile Spatial Interaction (MSI) [8] scenarios and smart glasses. Prototypes were developed as research tools and deployed in user studies to answer the research questions formulated in Section 1.2.

1.1 Design Space: From Non-Visual to Always-On Visual Interfaces

It has been shown that both the handheld form factor and visual interfaces result in competition for cognitive resources among multiple tasks in practical mobile conditions and lead to difficulties in interacting with information and inattention blindness. Unfortunately, the current attempts (on-device vibrotactile feedback and smart glasses) do not provide satisfying solutions. The formulated design approach in this research is thus to explore hand-based haptic interfaces to derive practical solutions in response to the highly dynamic nature of the mobile use cases.

This thesis encompasses three research areas in which the practical use cases are the most challenging on current interfaces and for which haptic solutions would benefit users the most (see Figure 1.2). Area I is developing expressive haptic stimuli and information encoding for mobile communication. The research goal is to increase the expressiveness of haptic stimuli so that visual attention is not required when interacting with information. Area II is to design interaction techniques for MSI [8] applications in which the surroundings constitute part of the content. This demonstrates the most contradictory scenario, in which people concentrate their visual resources onto visual interfaces instead of paying attention to their surroundings. Lastly, Area III is to extend the exploration of hand-based haptic interfaces for smart glasses, an extreme case in which a visual interface is always available for mobile use. Considering the fact that the concern of

social acceptability would stop users from deploying this technology, the research goal is to propose unobtrusive haptic solutions for interacting with smart glasses. The current mobile interface designs for the use cases in the three areas do not provide satisfying solutions, and the interaction is limited. Examining the areas from perspectives beyond the established interaction paradigms could potentially reveal more possibilities and help to derive novel solutions that can practically benefit the users. In the following sub-sections, I explain what the three research areas are and why they were chosen to be investigated.

1.1.1 Developing Expressive Haptic Stimuli

In Area I, the focus is on designing new forms of haptic stimuli for mobile communication aimed at increasing the expressiveness of the stimuli, in terms of both information capacity and accessibility. While capacity refers to the amount of information that can be conveyed through the stimuli (or how informative the stimuli are), the accessibility of the information refers to how easily the stimuli can be perceived. Although current mobile devices provide on-device vibrotactile stimuli for delivering information, the bandwidth and expressiveness are very restricted, especially in mobile conditions [31].

Research in this area seeks more expressive haptic solutions for encoding information in practical mobile contexts. The thesis explores solutions inspired by organic user interfaces (OUIs) [37] and shape-changing interfaces [78], which can provide static and continuous variation in physical forms that enable users to perceive the form by touching without looking. Compared with vibrotactile stimuli, this type of cutaneous and kinesthetic feedback through deformation is potentially easier to perceive under mobile conditions, whether in a pocket or when the users are moving, and is hence more expressive.

1.1.2 Designing Mobile Spatial Interaction with Surroundings as Content

Area II targets designing interaction techniques for MSI applications for which the surroundings constitute part of the content and dividing attention between the device and the surroundings would result in hampered mobility and experience. For example, the purpose of a tourist guide application on smartphones is to help users to gain knowledge about the points of interest (POIs) in front of them and to experience the surroundings. However, both the visual content and the touchscreen-based interaction can be so

intriguing that users concentrate on the handheld device, rather than on the surroundings. Solutions have been proposed from an interaction design perspective for engaging more with the surroundings. For example, the “magic wand” interaction technique on handheld devices enables users to physically scan the space for information [23], enabling direct focus on the surroundings. Magnusson et al. studied the use of directional pointing in an outdoor setting with a handheld device [59]. The participants in that study received vibration pulses for navigation when the device was pointed toward the next waypoint. They also developed a sophisticated mobile tourist guide in which users could scan for POIs with the handheld device with an additional distance-filtering feature through on-screen gestures [60]. Their audio-haptic interface enabled eyes-free interaction, and even visually impaired persons can use the application. Another “magic wand” example is a car-finder application that Pielot et al. developed [73]. Users reported that this type of interaction was easy to use and natural. However, the nature of a visual interface draws users’ attention back onto the device immediately after clicking the selection button [23]. Failure to maintain attention on the surroundings in these scenarios will result in distracting users away from the real content and detaching them from the immediate environment. Research in this area addresses the challenges in connecting users and the surroundings through interaction design for a more engaging and immersed experience.

Extending from the point-and-select interaction manifested in the “magic wand” technique, mid-air hand-gestural interaction was explored in this research area with the intent to utilize our existing skills in using our hands to interact with everyday objects while maintaining visual attention on the surroundings. A hand-worn haptic solution was developed to realize the idea of interacting directly with the surroundings using a hand without the mediation of a handheld device, in which real-world landmarks form the visual counterpart of the non-visual haptic interface. Furthermore, the haptic solution is able to represent the tangibility of distant and untouchable POIs on the hand.

1.1.3 Interacting with Always-On Visual Interface

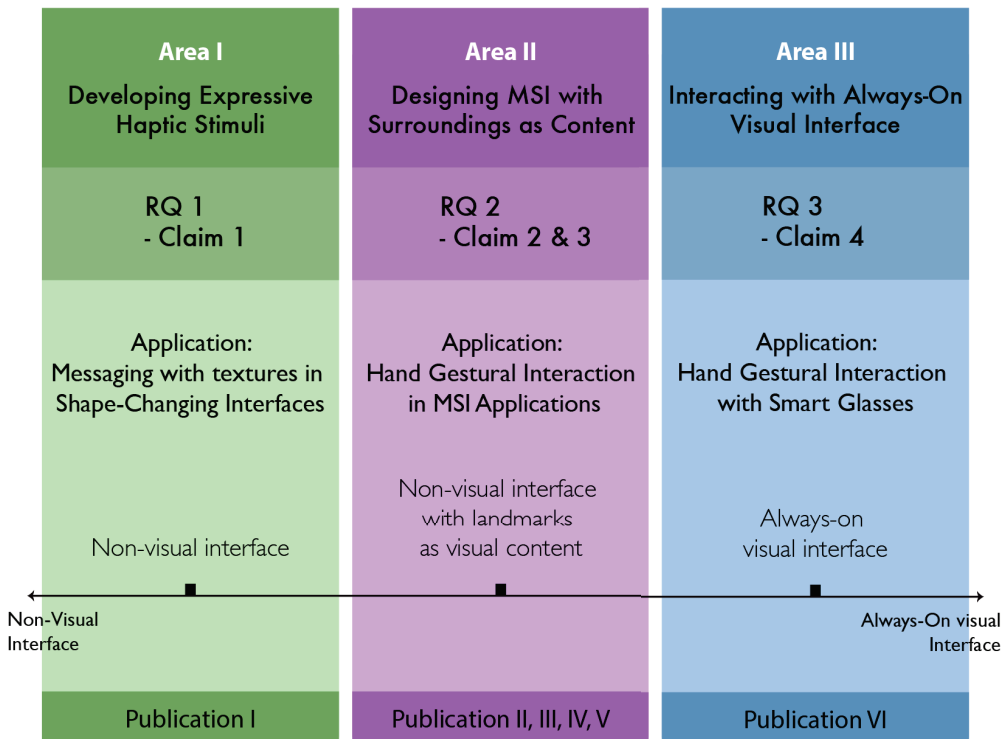
The previous two research areas target challenges resulting from the handheld form factor and the domination of visual interfaces on mobile devices in mobile contexts, to seek solutions that do not need visual attention on the interface. Research in Area III examines the extreme case of smart glasses, on which a visual interface is always available and accessible through hands-free and head-up interaction. The technology is designed to provide a per-

vasive visual interface and with additional benefits from the information being overlaid on the immediate environment, so that users can maintain their attention on their surroundings at the same time. Smart glasses could be an ideal solution to the issues mentioned earlier. However, the currently available interaction techniques, such as mid-air hand gestures and voice control, could raise concerns regarding social acceptability, preventing people from adopting this technology. Wearable solutions have been proposed. For example, Dobbelsstein et al. presented Belt, a touch-based input device to be worn around the hip, which the hands can easily and unobtrusively reach [18]. The participants in the study perceived the interaction as being socially acceptable. However, the application design was mainly for quick access to information and awaits further development. This thesis investigates the issue of social acceptability and compensates for its factors through interaction design, aiming at deriving an unobtrusive interaction techniques. Moreover, this thesis seeks to derive hand-based haptic solutions for increasing the tangibility of the untouchable visual interface on the smart glasses through providing tactile feedback on the hand and coordinating our proprioception of the hand with the visual feedback.

1.1.4 Summary of the Design Space

The scope of the research extends along the axis of the explicitness of the visual interface (see Figure 1.2). Area I examined the extreme case where there is no visual interface involved. The users can interact with the system only by touching, although viewing the interface is not prohibited. On the other extreme, Area III investigated interaction design for smart glasses on which the visual interface is even more dominantly presented to users and visual feedback can be explicitly given in response to the users' manipulation. In between the two, as opposed to being provided and generated by the system, the visual content is the appearance of the surroundings, which also constitute part of the content. In other words, the appearance of the real-world landmarks becomes the visual counterpart of the non-visual interface.

Mobile . Haptic . on the Hand



RQ 1: How can a shape-changing interface benefit users in mobile communication?

Claim 1: Shape-changing interfaces can benefit users by conveying information through static, continuous, and informative haptic stimuli.

RQ 2: How can a hand-worn haptic interface be designed for enhancing users' awareness of the surroundings in MSI scenarios?

Claim 2: The glove is an effective form factor for enabling mid-air hand-gestural interaction with haptic support in MSI applications.

Claim 3: Releasing visual attention from the interface and enabling mid-air hand-gestural interaction directly with the surroundings in MSI applications can achieve a higher-level experience of immersion in the environment.

RQ 3: How can a haptic interaction technique be designed for smart glasses to enable unobtrusive interaction?

Claim 4: Independent tracking and accurate recognition of hand gestures can enable unobtrusive and intuitive interaction with smart glasses.

Figure 1.2: This thesis investigates the three research areas for deriving feasible hand-based haptic interfaces.

1.2 Research Questions

For each of the three areas in the design space, one research question (RQ) was formulated accordingly (see Figure 1.2).

RQ 1: How can a shape-changing interface benefit users in mobile communication?

The first research question addresses applications in which information could be encoded with variation in shapes for communication purposes, considering both the capacity of information and perceptibility of the stimuli. A practical use case is to receive a message while on the move. Since the transitory nature of vibrotactile stimuli prevents users from perceiving the notification, other forms of haptic stimuli should be considered. Potentially, shape-changing interfaces can provide static and continuous stimuli, thus they may be more perceivable than vibrations in these conditions. In this use case, users can sense the information-encoded shapes even when on the move.

Publication I looks at two angles: how shapes can convey information and be perceived, and how the interface can fit in the compact size of a modern mobile device. Prototypes were developed as a research tool for exploring the possibilities of conveying information through textures. Moreover, in order to fit in the mobile context, the shape-changing mechanisms were further developed in the second iteration with the aim of deriving a compact size to augment modern mobile devices.

RQ 2: How can a hand-worn haptic interface be designed for enhancing users' awareness of the surroundings in MSI scenarios?

The second research question addresses applications in which dividing users' visual attention between the interface and the situated environment should be avoided. A practical use case in MSI is to use a non-visual haptic interface to interact with geo-referenced information in users' situated surroundings. Interacting with visual interfaces in MSI could result in less efficient intra-modal time sharing [105], since the users would need to split their attention between the interface and the surroundings. Alternatively, deploying haptic interfaces in MSI applications could potentially ease the competition for visual resources among multiple tasks, leaving visual attention on the surroundings. Furthermore, direct interaction with the surroundings by the hand could enhance the connection between the users and the surroundings, hence creating a more immersed experience in the environment. Similar to the "magic wand" interaction technique but with-

out being mediated by a handheld device, the haptic interface could enable users to point by hand and interact with the information while maintaining focus on the surroundings.

Publications II-V manifest the design and development journey of the SSH Glove-based haptic solutions. Publication II looks at the challenges and potentials of the derived SSH Glove. Beginning by seeking form factors beyond handheld solutions, Publication III illustrates the iterative development of the glove from scratch, while Publications IV and V demonstrate the design and benefits of the haptic system in practical MSI scenarios.

RQ 3: How can a haptic interaction technique be designed for smart glasses to enable unobtrusive interaction?

The above-mentioned challenges of interacting with modern mobile devices in mobile communication could potentially be eliminated by smart glasses, a wearable device that enables hands-free and head-up interaction. However, the method of interaction with smart glasses, such as voice control or mid-air hand gestures, could attract too much attention from bystanders, resulting in users' unwillingness to adopt this technology. The third research question specifically addresses this issue and investigates how a haptic interface could be designed to benefit the users.

Publication VI presents an in-depth survey on socially acceptable techniques, as well as a set of design principles for developing interaction techniques for smart glasses. The SSH glove was proven a feasible solution by enabling low-posture interaction with haptic support through an empirical study.

1.2.1 Claims

The answers to the research questions can be formulated as the following claims. Both Claims 2 and 3 answer RQ 2, and Claims 1 and 4 answer RQ 1 and 3, respectively (see Figure 1.2).

- Claim 1** Shape-changing interfaces can benefit users by conveying information through static, continuous, and informative haptic stimuli.
- Claim 2** The glove is an effective form factor for enabling mid-air hand-gestural interaction with haptic support in MSI applications.
- Claim 3** Releasing visual attention from the interface and enabling mid-air hand-gestural interaction directly with the surroundings in

MSI applications can achieve a higher-level experience of immersion in the environment.

Claim 4 Independent tracking and accurate recognition of hand gestures can enable unobtrusive and intuitive interaction with smart glasses.

Claim 1: Modern mobile devices have incorporated multimodal cues, such as auditory icons and vibrations, in delivering information. However, the transitory cues cannot be properly perceived in a noisy environment or when the user is moving. This thesis proposed deploying shape-changing interfaces as a more informative and expressive solution for mobile communication, considering their ability to present static and continuous stimuli. By manipulating the amplitude or granularity of the textures of the device surface, the shape-changing interfaces can present the textures as messages, which is then perceivable even when the device is in a pocket, eliminating the need to take the device out for visual contact. The claim is confirmed with empirical studies in which the mechanisms were developed to be compact enough for incorporation with existing mobile devices. Participants also presented a high shape-detection rate and were able to associate emotional information with the shapes.

Claim 2: In MSI scenarios, the user’s current location is exploited by the system to provide relevant information regarding the surroundings. As the “magic wand” technique can be used for scanning for geo-referenced information distributed in the environment [23], the handheld form factor requires the user to carry an additional device in the hand, thus downgrading the degree of freedom. Moreover, while the tactile feedback support on the device is only rudimentary, the interaction is also confined to pointing and clicking due to the limited capability in recognizing more sophisticated hand gestures. This thesis explored new form factors and argued that the glove form factor can be a beneficial solution for MSI scenarios. The glove form factor was proposed because it affords sufficient space for distributing sensing technologies and actuators on the essential parts of the hand, enabling accurate gestural recognition and tactile feedback directly on action-performing bodies. Therefore, the interface enables users to interact directly with real-world landmarks through mid-air hand gestures as if they were interacting with everyday objects. Empirical experiments from the laboratory to the field were conducted to validate the design of the system.

Claim 3: In MSI scenarios, a touch-based visual interface is another factor that contributes to inattentional blindness, or even worse, separation

between users and their surroundings. Even though the “magic wand” technique demonstrates a good example of enabling a direct focus on the environment, the users’ attention is soon drawn back to the device in order to interact with the information through the touchscreen. This research proposed the integration of the SSH Glove with an audio modality for MSI applications to maintain the user’s visual attention to the surroundings. Moreover, as users interact directly with the surroundings through mid-air hand gestures, a higher-level experience of immersion in the environment can be achieved. This claim is confirmed with an empirical investigation in which the glove system was compared with a touchscreen-based interface in an MSI application. Manifested in this part are the differences between the experiences and reasons why a higher level of immersion can be achieved.

Claim 4: Smart glasses seem to be a promising solution to the difficulties of interacting with information in mobile settings and the issue of inattentive blindness. Even though smart glasses provide a dominant visual interface, the see-through interface enables users to remain focused on the environment. However, currently available input techniques for smart glasses either cause users to have concerns about social acceptability or downgrade the degree of freedom. This thesis shows why smart glasses cannot be broadly adopted from an interaction design point of view and argues that they can be complemented by the SSH Glove, which enables unobtrusive interaction.

1.3 Structure of the Thesis

Continuing the groundwork laid in this introductory chapter, Chapter 2 provides an overview of the background and related works for developing haptic solutions further in the three research areas. The research methods are presented in Chapter 3. The development of haptic solutions and the related empirical studies are presented in Chapters 4, 5, and 6, each of which addresses one research question. The findings of the studies are presented in each chapter as well. Chapter 7 concludes the research and presents the limitations and implications.

Chapter 2

Background

As illustrated in the introduction, there are two major problems users encounter when interacting with information in modern mobile environments: 1) difficulties in interacting with information on the move due to the hand-held form factor and the visual interface deployed, and 2) inattentive blindness. This thesis argues that exploring hand-based haptic interfaces can achieve effective solutions. The main approach adopted is to explore hand-based haptic interfaces aiming for developing interaction techniques that require no visual attention on the interface so that the visual resource can be reserved for the highly dynamic mobile environment. As introduced in the previous chapter, three areas spanning the design space were examined for designing interactions in practical mobile contexts: 1) developing expressive haptic stimuli, 2) designing mobile spatial interactions with surroundings as content, and 3) interacting with an always-on visual interface. This chapter gives an overview of the background and related works, followed by a summarizing subsection with concluding remarks.

2.1 Attention and Visual Dominance

The intriguing content and touchscreen-based interaction are not the only factors responsible for occupying our visual sense. Vision is typically the dominant sensory modality that humans rely on [15, 77]. Colavita [15] conducted an experiment on visual dominance in which participants pressed a button whenever they saw a light and another button when hearing a tone. In most trials, only one stimulus presented unpredictably, while in few trials, both stimuli presented simultaneously. Participants were able to respond to unimodal stimuli accurately and rapidly. Surprisingly, in bi-

modal trials, participants almost always responded to the light only. Some did not even notice the presence of auditory stimuli in bimodal trials.

Under some conditions, such as an increased level of visual noise, visual dominance could be shifted to other modalities. Ernst et al. [19] presented a study in which participants discriminated the variance of the height of a raised ridge through looking and/or touching. While the visual appearance of the ridge was presented through the reconstruction of binocular disparity with liquid-crystal shutter glasses, the haptic stimuli were presented with force-feedback devices. They found that, while our nervous system integrates both visual and haptic information to estimate the properties of an object, the variance of the estimation in each modality has an effect on deciding which modality dominates. As the noise level increased in visual stimuli, the dominating modality shifted from vision to haptic. A later experiment further identified the two-way adaptation between vision and haptic: when haptic was more reliable, vision adapted to match haptic, and vice versa [10]. The possibility of shifting the dominance from vision to haptic supports the decision of choosing haptic interfaces to be explored in this research.

The phenomenon of visual dominance appears to be the result of weak capability of the visual sense in detecting alerts [49, 76], meaning that humans are poor in noticing visual changes. Therefore, to compensate the poor visual alerting mechanism, humans keep their attention tuned to the visual channel. Moreover, distracted visual attention has a negative effect on vision-based estimate. Following Ernst et al. [19], Helbig et al. conducted an experiment in which an additional visual task was introduced when estimating the size of a ridge through vision and/or haptic [33]. They found that the vision-based estimates were more affected by the second task than the haptic-based estimates. In this case, the chances of inattentional blindness also increased due to the extra demand on attention [90]. The results resonate well with the multiple resource model, that time sharing is poorer intra-modally than cross-modally [105].

2.2 Haptic Stimuli Beyond On-Device Vibrotactile Feedback

In general, haptics refers to “*sensory and/or motor activity based in the skin, muscles, joints and tendons*” [109]. Under the umbrella term, there are two subsystems: touch (tactile/cutaneous) and kinaesthesia (kinaesthetic). While tactile sensors enable humans to perceive stimuli on the skin, such as temperature, texture, and vibration, proprioceptive sensors

provide us with information regarding body position, force, and motions [58]. For example, proprioception also enables humans to assess the weight of an object and the direction/angle/position of the hand. As tactile sensors are mostly located under the skin, the receptors of proprioceptive sensors are embedded in muscles, joints, and tendons. In the thesis, both cutaneous and kineasthetic aspects of haptics are considered.

As illustrated in the introduction, the on-device vibrotactile stimuli are transitory and cannot be easily perceived in mobile conditions. Even though there has been research in manipulating vibrotactile parameters in increasing the bandwidth for information encoding and messaging, such as research in tactons [9], the dynamic nature of the mobile environment still prevents transitory stimuli from being reliably detected.

Unlike vibrotactile feedback, the haptic feedback from Organic User Interfaces (OUIs) or shape-changing interfaces can be static and continuous, thus it is potentially more expressive and suitable for mobile communication scenarios. OUIs have non-planar displays that may actively or passively change shape via analog physical inputs. Some aspects of OUIs could be considered haptic interfaces because they provide cutaneous and kinesthetic feedback through shape-change. Any physical movement of a part of the interface can provide haptic feedback to the user. Furthermore, OUIs also make use of haptic input. Deformations tend to be triggered through various forms of touch manipulation: pressure, twisting, and tapping [78]. Research in this area has produced interfaces that can change their orientation, form, volume, texture, viscosity, spatiality, adding/subtracting, and permeability [78]. Roudaut et al. have also summarized the shape-changing parameters as size, shape, amplitude, porosity, granularity, speed, and strength [83]. To further use these parameters as a communication channel, it is important that users can distinguish and identify multiple levels of these parameters. In terms of mobile device interaction, one of the most promising shape-change parameters is texture because the overall shape of the device is not affected [31], indicating that it is possible to augment an already existing rigid device, such as a mobile phone.

Various actuators have been deployed in modulating textures. Dimitriadis and Alexander developed several different types of shape changes for mobile alerts [16]; the most successful of which was the protrusion device, which has a small arm protruding from the display. The protrusion was presented either as a static stimulus or with a slow or fast pulse. The results showed that participants could detect 100% of these alerts in their pocket. Wagner et al. built a 6x6 tactile shape display that uses servo-motors to

control metal pin array [100]. Experiment results showed that participants could distinguish 3D vertical lines when the pins were covered with a rubber layer. However, given the large number of motors in the display, the prototype was not suitable for mobile use. Hemmert et al. created Dynamic Knobs as a means of tactile interaction with mobile phones [34]. The knob extends from the side of the phone to display information. It can also be used as an input device, as it can sense pressure. Similarly, Pasquero et al. presented THMB on which an array of piezoelectric actuators mounted on the side of the device functions as tactile display stimulating the skin of the thumb by lateral deformation [73]. Meanwhile, the interface can detect both sliding and detent gestures. Combining an LCD screen and the tactile display, THMB can support multimodal navigation of scrolling applications. Coelho et al. proposed an actuated surface called Surflex [14], which can change shape to display ambient information. The surface is made up of Shape Memory Alloys (SMA) and foam. Harrison and Hudson also proposed that texture displays could be used to provide passive tactile feedback on the surface of various different objects [31]. User evaluations showed that texture displays with material that bunches into a series of ridges (amplitude changes) resulted in higher recognition rates than those with striated features that spread out when stretched (area changes). Their results are very promising, but there was no discussion of how the proposed texture display could be integrated with a mobile device and no specification of the exact textures created along with their perceptual thresholds.

In terms of applications, some recent research has examined the use of shape changes for mobile device alerts [16]. Alerts presented by shape changes were compared to vibrotactile alerts. The results showed that shape changes were more noticeable and preferred by users. This suggests that deformations could be effective and perceivable in mobile environments, where a wide variety of applications could be developed.

2.3 MSI Hardware Solutions Beyond the Handheld Form Factor

The handheld form factor of mobile devices needs to be re-considered for MSI scenarios, as explained in Chapter 1. Today's sensor-rich mobile devices have enabled people to interact with physical places or objects that are augmented with geo-referenced digital information [8, 23]. Meanwhile, the relationships between people, their current geographic location, and their devices are summarised as MSI [8], in which new opportunities have been opened for designing the interaction in between. For example, com-

binning the users' location and the orientation of the device, the system can understand where the users are pointing with the device in the hand. This is an explicit way to interact with the surroundings since users can express their immediate interest through pointing, as seen in the "magic wand" and "smart lens" interaction paradigms introduced by Fröhlich et al. [23]. In one of their envisioned scenarios, users can point with a mobile device at a real-world landmark and can directly interact with the associated information by touching a button on the device. This point-and-click interaction can enable a direct focus on the environment. Hence, an intimate connection between the user and the surroundings can be constructed. MSI applications that utilise pointing with handheld devices can be found in tourism [93] and the exploration of surroundings [82, 108]. However, the benefits of the handheld device come at the cost of carrying an additional device in the hand and keeps people from using that hand for other tasks, which downgrades the degree of freedom due to the competition for motor resources [70]. Moreover, in terms of the naturalness in the interaction, other than pointing, a handheld device fails to accurately reflect hand gestures in all dimensions, which results in a confined gestural vocabulary. As using a bare hand for distant pointing and clicking is advantageous [99], this research seeks more sophisticated mid-air hand-gestural tracking technologies and a suitable form factor for enabling natural hand-gestural interaction in MSI applications.

As a form of kineasthetic haptic interaction, mid-air hand gestures have the potential to enable a natural and intuitive experience of interacting with computers by leveraging users' existing skills at interacting with everyday objects, which is the core idea of natural user interfaces [91, 106]. Such interactions are especially useful when the interface is distant (as with large displays) or even disappearing (as with immersive systems or ubiquitous environments), while instrumented interaction techniques, such as keyboards and mice, become cumbersome in these cases [79]. Mid-air hand gestures have been widely deployed in controlled environments, such as for virtual reality (VR) or immersive systems, in which hand tracking commonly relies on computer vision [6, 99, 101]. These fixed infrastructures not only require users to perform the gestures within the camera's viewing angle, but also suffer from occlusion issues; this limits their use in MSI scenarios.

Alternatively, tracking technologies can be deployed in wearable form factors to maintain the user's mobility in MSI scenarios. Typically, the form factors for hand tracking can be a ring, a wrist- or armband, or a glove. Merrill and Maes investigated such interaction techniques [65], leveraging natural looking, pointing, and reaching behaviours in interac-

tions with the combination of digital information and physical objects. The proposed wireless system can be worn on a finger to track pointing orientation. However, it is based on infrared and requires extra transponders to be distributed in the space, which would be impractical when deployed on a large scale. Myo is an example of an armband hand-tracking technique [30]. It utilises electromyographic and inertial measurement units (IMU) as core sensing techniques, and it can wirelessly communicate with other systems; thus, it can potentially be used in outdoor and mobile contexts. However, detecting subtle or complex gestures involving finger movements seems to be challenging. As a result, it deploys unnatural gestures, such as opening the palm to indicate a click, in its interaction. Digits [48] is a wristband consisting of infrared cameras that can reconstruct the hand's full 3D pose. More examples exist of cameras worn on other parts of the body, such as on the neck [47] and the thighs [54], to sense hand gestures. However, these computer vision-based technologies cannot avoid occlusion issues. In principle, if a sensing technology fails to reliably recognise a large set of common and natural gestures, its users will likely need to spend extra effort to learn the (possibly unnatural) gestural vocabulary that the system can recognize. The glove form factor appears well suited for direct pointing and sensing subtle hand postures. For example, IMUs and flex sensors can be easily mounted on individual fingers to detect finger actions [39, 84]; hence, hand postures can be accurately captured to construct a more natural gestural vocabulary.

The glove form factor also affords sufficient space on the hand to be exploited for feedback. For example, mounting actuators on relevant parts of the hand allows tactile feedback to be presented directly on action-performing bodies for delivering abstract information and physical object properties [12], which is not possible on handheld form factors. Scheibe, Moehring, and Froehlich presented a haptic glove prototype for VR applications [86]. The tactile feedback in the glove was given to the fingertips to simulate contact with virtual objects. More recent variants of the haptic glove paradigm are the v-Glove [24] and AHNE [97]. Tactile feedback in both cases was built for increasing the tangibility of the untouchable interfaces in virtual environments.

Tactile feedback applied on the hand can also be used for facilitating pointing in target-acquisition tasks when encoded with directional information. For example, Oron-Gilad et al. conducted a sophisticated study on deploying vibrotactile guidance on the hand for pointing at targets with an inertial mouse on a computer display [68]. They found that both time and accuracy were improved with the cues. Lehtinen et al. presented an evalua-

tion of enhancing on-screen visual search with tactile guidance provided by four palm-based actuators [53]. They evaluated the added value of tactile guidance in distinguishing a specific target from others with a close resemblance to it. Their findings also suggest that pointing with tactile guidance enhanced the visual search task. It should be noted that abundant research can be found on tactile guidance using other form factors, such as belts. This type of technique usually consists of vibrotactile actuator arrays that are evenly distributed around the waist, thus affording directional guidance towards the vibration [3, 20, 92]. Similarly, placing actuators around the wrist for pedestrian navigation is gaining more interest as smart watches become more and more popular. For example, Dobbstein et al. have developed tactile navigation provided on the wristband of a smart watch [17]. While these systems have significant merits when used in navigation systems or in the design of directional vibrotactile feedback, they have not been designed for direct interaction with the surroundings.

While hand gestures are a form of kinaesthetic haptic interaction, the tactile feedback presented on the hand constitutes the cutaneous counterpart of a haptic interface. The above-mentioned technologies have shown that a glove form factor can potentially enable the construction of a natural gestural vocabulary and enhance performance through providing tactile guidance on the hand.

2.4 Do Smart Glasses Solve the Problems?

Potentially, head-mounted displays, such as smart glasses, could be an ideal solution to the issues illustrated in the introduction. The wearable form factor enables hands-free interaction and provides always-on access to information while maintaining a high degree of freedom. The see-through visual interface enables head-up interaction while maintaining the awareness of the environment. However, the concern of social acceptability could largely affect users' willingness to adopt a technology [50, 55, 88, 96]. For example, using voice control, as on Google Glass, can arouse much attention, especially in a quiet shared environment, and could even disturb others. Another popular option, using mid-air hand gestures at eye level, has even more social implications, such as if the user points at a person. The concern of social acceptability was further confirmed by Tung et al., who asked a group of participants to build a set of command gestures for games on smart glasses in a public space [96]. The majority of the gestures performed were oriented toward the chest area rather than toward the face, mainly to avoid attracting too much attention from bystanders.

To avoid getting too much attention, there has been research in developing interaction techniques that involve only slight muscle movements. Epson Moverio and Sony SmartEyeglass have a wired handheld device with a trackpad attached to the glasses. Although subtle finger gestures are possible on the device, this design requires users to carry an additional device in the hand, which not only hampers mobility but also is known to be less preferred with respect to mid-air gestures [96]. Gaze input [87, 95], and facial gesture detection [25] have also been integrated with head-mounted displays. Although only slight muscle action is involved in the interaction, which could reduce obtrusiveness, the technology requires excessive calibration and is prone to tracking errors. Ishimaru et al. [41] also proposed a technique combining the detection of head movement and eye blinking frequency to recognize users' high level activities, such as distinguishing reading from talking. Although the recognition rate can be as high as 82%, further development is needed for input purposes. Moreover, head gestures might not be preferred if hand gestures are available [51]. Touching on the body can be of less concern regarding social acceptability since people often do it unconsciously. Various techniques have enabled on-body gestural input and could be integrated with smart glasses [32, 80, 104]. Earlier studies have shown that gestures performed on the body and their locations result in different perceptions of social acceptability [77, 88]. As reported by Tung et al., touching on the palm is a preferred option (51%) [96]. An example is PalmType [102], which enables users to type with a finger on the palm. However, the interaction might be limited with touching events, and both hands would be required in the case of PalmType.

Although hand gestures might have more social implications in various contexts, they have the potential of enabling natural and intuitive interactions. Tung et al. found that mid-air gestures were preferred over on-body or on-device gestures when interacting with smart glasses [96]. Mounting the gestural sensing technology on the glasses could be a compact and convenient solution, as can be seen on Microsoft HoloLens. However, the gestures are required to be performed within the camera viewing angle, which is high at eye level, and can attract much attention. On the other hand, separating the sensing technology from the glasses could avoid obtrusive action on the eye level, as manifested by Belt [18] and ShoeSense [4]. Previous studies have also explored various form factors worn on different parts of the hand for embedding sensing technologies. For example, sensors can be worn on the fingers [43, 107], wrist [72], forearm [30, 62], or whole hand [21]. Ideally, having the sensors directly on the hand makes the tracking of hand gestures more robust than with computer vision-based tracking.

While arm-based techniques such as Myopoint [30] can track pointing and rudimentary gestures, gloves can track more fine-grained gestures, such as bending individual fingers. Moreover, as illustrated in the last section, the capability of embedding actuators on action-performing bodies also suggests the adoption of the glove form factor for this untouchable interface on smart glasses.

2.5 Summary

This section summarizes the literature review with concluding remarks. From the literature in Area I, it could be concluded that:

- On-device vibrotactile stimuli have been adopted as a haptic solution to confront the drawbacks of the visually dominated interface on mobile devices. However, the transitory stimuli are not always perceivable in mobile conditions.
- Shape-changing interfaces afford static and continuous stimuli that can be more expressive than vibrotactile feedback when on the move.
- Multiple shape-changing parameters can be utilized for encoding information, among which amplitude change is a potentially more effective method.

However, there has been little related work in addressing shape-changing interfaces for practical mobile communication purposes. Shape-changing mechanisms are normally large in size or power-consuming, thus they are more challenging to make mobile. Moreover, the information conveyed over shape-changing interfaces is often implicit. The capability of conveying information over shapes for mobile communication requires more investigation. RQ1 addresses the gap in which shape-changing interfaces are to be designed for mobile communication purposes. Practical knowledge required for answering RQ1 would include the information encoding on the shapes, the users' perception, and the portability of the interface.

The literature review in Area II can be summarized as:

- Modern mobile technologies have enabled people to interact with physical surroundings that are augmented with geo-referenced digital information.
- As can be seen from the “magic wand” technique on handheld devices, users benefit from direct interaction with the surroundings and keeping their visual attention on the environment.

- The benefits of handheld devices, however, come at a cost of occupying the hand and downgrading users' mobility. The devices also fail to accurately recognize hand gestures, resulting in a limited gestural vocabulary beyond pointing and clicking.
- Alternatively, the glove form factor affords accurate recognition of hand gestures, as well as providing tactile feedback on action-performing bodies.

Although there has been research on hand-tracking techniques and applications with the glove form factor, most studies have been designed for indoor, controlled environments. It has been shown that the "magic wand" technique could help users focus on the environment, though only for a short moment before the users shift their focus onto the screen. The gap, which is addressed by RQ2, is whether hand-gestural interaction enabled by the glove form factor can also help users focus on the environment. The practical knowledge required to answer RQ2 includes techniques for deploying hand-gestural recognition for outdoor use and how people can associate the action of the hand with the environment.

The literature in Area III has shown that:

- Although smart glasses could potentially be ideal for MSI, the interaction techniques raise concerns regarding social acceptability and make people unwilling to adopt this technology.
- By requiring only slight muscle action or avoiding eye-level interaction, the interaction techniques developed for smart glasses could avoid attracting too much attention from bystanders; hence lowering the concern of social acceptability.
- Isolating tracking techniques from the glasses can effectively avoid eye-level interaction.
- Mid-air hand-gestural interaction could potentially benefit smart glasses users for enabling intuitive interaction.

Although mid-air hand-gestural interaction can have more implications on social acceptability, it has the benefit of enabling intuitive interaction. As suggested in the literature, hand-gestural interaction might be more socially acceptable if eye-level interactions were avoided. RQ3 addresses the opportunity of designing and developing an unobtrusive hand-gestural interaction technique for smart glasses.

Chapter 3

Research Methods

The general research method in this thesis is to develop interactive prototypes as research tools to enable real-world interaction to take place. This can be an effective way to examine the proposed solutions in practical scenarios to inform future designs. A set of studies was conducted along this line of research that finally led towards this goal. This chapter provides an overview of the criteria for selecting research methods in each of the three areas, followed by the rationale for the experiment design where the prototypes were deployed.

The primary criterion for selecting a research method, as proposed by McGrath [64], is to maximize the following three desirable features in the collected research evidence: 1) generalizability of the data over the population of subjects, 2) precision of measurement of the behaviors that are being studied, and the control of extraneous factors that are not being studied, and 3) the realism of the situation or context within which the experiment is conducted as compared with the context to which the evidence is to be applied. Obviously, it is almost impossible to maximize all three features simultaneously, since these features fall at different levels of control and increasing one would result in reducing another. Depending on the goals and research questions of each study, this criterion was utilized for designing feasible experiments to derive valid research evidence. The experiments presented in this thesis manifest the maximization of the different features.

Based on the level of control, experiments can also be categorized as the following four types, from high level of control to low: 1) laboratory experiments, 2) analog experiments, 3) quasi-experiments, and 4) natural experiments [69]. Both laboratory and analog experiments are conducted in laboratory environments, but analog experiments deploy simulations of real-world conditions. Quasi-experiments and natural experiments, on the other hand, are conducted in the field. As natural experiments have the least con-

trol and the variation of a factor occurs naturally, quasi-experiments expose the experimental intervention in the field with limited control [69, 89]. The experiments presented in the thesis had different designs at different stages in the development of the solutions. In the following, I give an overview of the research strategies applied in the three areas considering the above criteria.

3.1 Research Strategy in Area I

As mentioned earlier, the expressiveness of haptic stimuli in this context can be seen from two perspectives: accessibility of the stimuli and the capability of conveying information, which are the two main focuses of this research. To understand how shape-changing stimuli can be well perceived, shape-changing mechanisms were developed to enable the manipulation of the amplitude and granularity of the texture. In this way, we aimed to understand what the limitations are for people to perceive not only the presence of stimuli but also the accuracy in detecting different magnitudes of stimuli (the perceptibility of stimuli). The results are the groundwork for further encoding information. The research also discovered that textural change can be used for encoding emotional information for interpersonal communication (the capacity of information), which was derived through post-study questionnaires.

The experiments were conducted in a laboratory, since at this early stage of the unimplemented system, conducting laboratory experiments has the practical advantage of reducing costs as compared to field experiments [38, 69] (see Publication I). Moreover, maximizing the precision by controlling as many extraneous factors as possible would also increase the validity of the results, which are fundamental knowledge for further development.

3.2 Research Strategy in Area II

Since the aim was to derive solutions feasible for practical mobile conditions, realism was the primary feature to be maximized when selecting the research methods. However, as the development of the haptic solution in Area II is divided into four stages, the beginning research stage focused on improving the precision by minimizing the effect of extraneous factors before shifting the focus to realism in later stages. In terms of experiment type, the first experiment was conducted in a laboratory environment, while the later ones were quasi-experiments in the field. The prototypes of the SSH Glove were developed iteratively throughout the stages.

The first stage was to observe the natural hand pointing posture to inform tactile guidance design, as well as to compare the performance between tactile guidance presented on the palm and on the fingers (see Publication III). At this early stage of the unimplemented system, the experiment was conducted in a laboratory to maximize the precision by controlling as many factors as possible. Although the ultimate goal was to deploy the system in urban environments, the first experiment was constructed with artificial markers as targets in the low-level target acquisition task in which unessential features were removed to reduce variation [38]. The strategy at this stage was to verify that the concept of tactile guidance on the hand for supporting mid-air pointing was feasible before further development for urban environments.

In the second stage, the experiment was conducted in a real environment where the real-world landmarks were deployed as targets in the acquisition task (see Publication III). The improved system gave tactile guidance to participants for locating a POI in their surroundings. Conducting the experiment in the field enabled a more genuine experience in practical situations; hence it was more realistic. To find the balance between maximizing the realism and the precision in the experiment, the experiment was chosen to be conducted with the user confined to a stationary location, since there were still essential factors that needed to be investigated. The results regarding tactile perception and performance derived from the first stage could be generalized to a low-level application, but were not necessarily feasible in practical situations. For example, the artificial targets in a laboratory could be very different in the field, and it was not clear whether people could identify the landmarks as designated targets or not. The experiment was thus designed as a quasi-experiment in which there were more factors less controlled because they were influenced by reality.

The third stage progressed to an even more realistic scenario in which users were on the move (see Publications III and IV). As a recommendation application for tourism, the proposed audio-haptic (AH) system guided the participants to point at a nearby POI while they were walking in the area. This was a quasi-experimental design in which realism was to be maximized. Not only was the experiment setting similar to a real scenario, but also the recruited participants were all tourists who had little knowledge about the environment. Moreover, although the glove was specially made, the core technologies deployed (e.g., Global Positioning System (GPS)) were common and standardized, which was easy to generalize or extend to other applications. As pointed out by Hornbæk [38], a strong baseline in this kind of study is important, thus a touchscreen-based application was

deployed as the baseline in the experiment. By incorporating this baseline, the experiment could directly show the difference between the two very different interaction paradigms in practical use cases. The chosen baseline was well justified, since it manifested the two main causes, i.e., handheld form factor and visual interface, of the problems argued in this thesis.

In the last stage, realism was still the feature to be maximized in the selection of the research method, since the ultimate goal was to derive practical solutions for increasing the user's awareness of the surroundings (see Publication V). In this research, the limitations and constraints of the glove-based AH interface were addressed, and the visual and AH interfaces were not seen as mutually exclusive. A haptic solution could be even more feasible for practical conditions if complemented with Augmented Reality (AR), which is a common and popular technique for the same purpose. Since both AR and the proposed glove-based AH solution were based on point-and-select interaction, presumably the integration could result in a more adaptive solution to the dynamic mobile conditions. The research method was to develop a system on which both AH and AR interfaces could co-exist as a research tool. The experiment was again a quasi-experiment where the participants experienced the system in the field and were exposed to many extraneous factors with limited control. A 2D map application on a touchscreen was adopted in the experiment as the baseline. Even though AR relies also on touchscreen-based interaction, aligning the pointing orientation and the target in real space is essentially different than interacting with the map on the screen. The experiment was conducted in the field, and the participants were free to move during the experiment so that the least level of control could be applied.

3.3 Research Strategy in Area III

The research on Area III aimed at developing an unobtrusive haptic solution for interacting with smart glasses. The sensing technology on the SSH Glove is independent from the smart glasses, which could potentially enable hand-gestural interaction in a low, unobtrusive posture. The prototype was then integrated with smart glasses for further investigation regarding social acceptability when using the technology.

The evaluation of social acceptability was based on a set of well-cited questionnaires [81], through which participants indicated their projected willingness when using gestural interaction in front of different audiences and in various places. Specifically, video clips of a person performing the gestures were presented to participants as stimuli for them to answer

whether they would be willing to perform the gestures in the specified conditions in the questionnaires. Considering the fact that the concern of social acceptability is mainly a subjective feeling, the strategy in this research was to maximize realism in the experiment design so that authentic subjective feelings could be derived from the genuine experience, hence generating more valid responses to the questionnaires. This quasi-experiment was conducted in a public space, exposing the participants to attention from the bystanders (see Publication VI). Participants were given several tasks in which they used the glove to interact with the smart glasses. Instead of simply watching the pre-recorded video stimuli, the participants were able to use the interface in public before answering the questionnaires regarding social acceptability.

The glove functioned mainly as an input device for smart glasses; thus, input performance was also one of the key measurements in this research. Since smart glasses afford unlimited mobile applications, low-level tasks were chosen to be adopted in this experiment. As Hornbæk [38] suggested, using elementary, low-level tasks in experiments can reduce variation and remove non-essential features of a task. Moreover, it ensures that if users are unable to accomplish the designated simple tasks, higher-level tasks will be equally or more difficult for users. The low-level tasks chosen were selecting a single item from many, scrolling through content, and typing. The tasks were decontextualized so that fewer cognitive functions would be needed and the effects of non-physical factors would be minimized. For example, in selecting a single item from many, the targets were standardized and marked with only numbers in order. Participants were then asked to select a target with the designated number. In the typing task, transcription was used to avoid extra cognitive functions required from the participants to generate text. The transcription was randomly selected from a well-established phrase set for evaluating text entry in HCI by MacKenzie and Soukoreff [57]. Results from the low-level tasks lay solid groundwork for developing higher-level applications.

Chapter 4

Messaging with Textures on Shape-Changing Interfaces

Research in Area I aims at answering the first research question: **How can a shape-changing interface benefit users in mobile communication?** Publication I reports the development and evaluation of a shape-changing mobile interface that can change the texture of the surface to present information. In the study, two types of shape-changing mechanism were developed for mobile use. As mentioned earlier, the expressiveness of haptic stimuli encompasses the capacity (how informative the stimuli are) and accessibility (how perceptible the stimuli are) of the information. Publication I thus incorporates the two parts, how well people can recognize the shape changes in amplitude and granularity, and what kind of information can be conveyed by the stimuli. The two-stage development of the shape-changing mechanisms, from table prototypes to mobile setting, was also reported in Publication I.

The results of the study showed that very low frequency texture changes can be distinguished with a high level of accuracy. Since the magnitude of texture change is small, the physical space required by the mechanism can be compact enough for mobile use. Moreover, participants could associate the textures with emotional information as interpersonal messages. Results from the study answer RQ1 and could be concluded as:

Claim 1 Shape-changing interfaces can benefit users by conveying information through static, continuous, and informative haptic stimuli.

4.1 Design of the System

This section describes the design and construction of the shape-changing interface prototypes, UnCovers (Undulating Covers), for manipulating both the amplitude and granularity of textures on a surface. Two types of mechanism were explored: a Pin Array and a Mylar UnCover. While the Pin Array UnCover was driven by servomotors, the Mylar UnCover presented a diamond-like pattern when axial compression was applied to a cylinder.

The prototypes in the beginning stage were designed as a research tool for investigating people's ability to distinguish amplitude and granularity changes, thus optimizing the size of the prototypes was not the first priority. The first Pin Array UnCover was driven by individual servomotors so that the height of each pin could be well controlled (see Figure 4.1 (a)). Meanwhile, the first version of the Mylar UnCover was simply three cylinders manifesting different levels of amplitude and granularity (see Figure 4.1 (b)). These two prototypes were deployed in the experiments. Two additional UnCovers were built for realizing the mobile use of these types of shape-changing interfaces. While the Pin Array UnCover was transformed into four sinusoidal ridges driven by one single servomotor (see Figure 4.1 (c)), the Mylar UnCover was realized by bending a small flexible cylinder driven by muscle wires (see Figure 4.1 (d)). Both demonstrated a compact size feasible for augmenting mobile devices.

4.2 The Studies

The perception of texture changes in amplitude and granularity were studied in two separate experiments. The first experiment was designed to investigate the perception of the amplitude changes. The first Pin Array UnCover was deployed for its capability of controlling the amplitude with higher precision. An adaptive staircase method, One-Up Three-Down method 31FC [52], was adopted. In each trial, three amplitudes were presented, in which there was only one target amplitude to be identified. The magnitude of the amplitude was increased after one incorrect response and decreased after three consecutive correct responses. This way, the accuracy of detecting different amplitudes could be derived. In this experiment, the independent variable was the amplitude of the shape change. Seven different amplitude levels were used: -3mm, -2mm, -1mm, 0mm, 1mm, 2mm, and 3mm. The effect of visual feedback was also studied. In one condition, the participants were able to see the shape change occurring, while in the

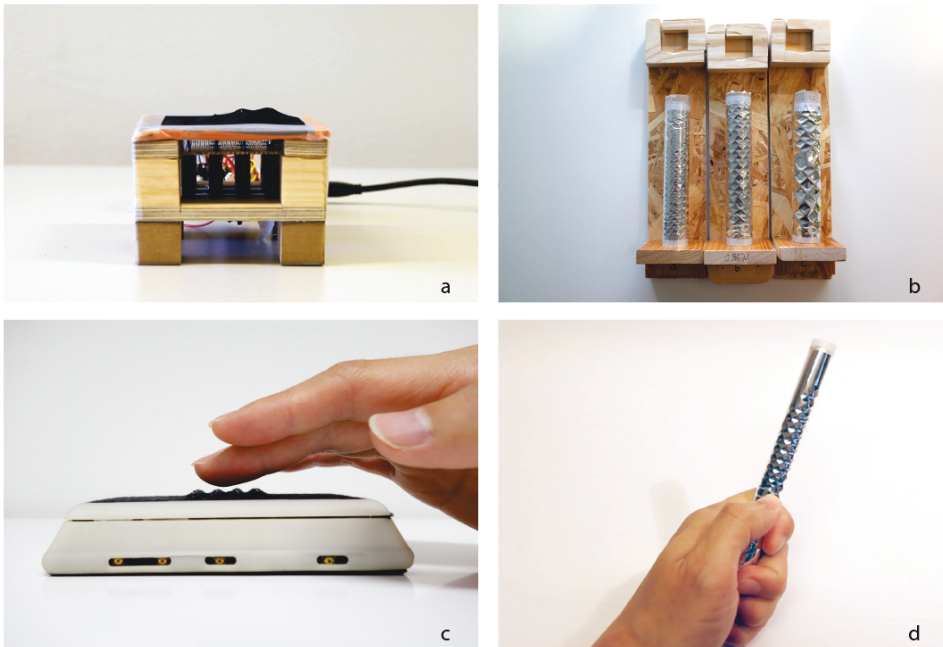


Figure 4.1: Variations of the UnCover prototypes. a) The first version of the Pin Array UnCover, b) the first version of the Mylar UnCover, c) the mobile version of the Pin Array UnCover, d) the mobile version of the Mylar UnCover

other, the UnCover was placed under a box so that the texture change could only be perceived through touching.

The second experiment was designed for investigating how well people can perceive texture changes in terms of granularity. The first versions of both the Pin Array and the Mylar UnCovers were deployed in this experiment. In each trial, two granularities were presented to the participants in a counterbalanced order. After examining the stimuli, the participants were asked to identify the stimulus with the larger granularity. For each UnCover, three different levels of granularity were involved. Similar to the previous experiment, there were two conditions, with and without visual feedback.

4.3 Findings and Claims

The results from the first experiment on the amplitude change showed that, in general, the detection accuracy was high. Both concave and convex amplitude at 3mm had more than 90% accuracy. Moreover, the higher the amplitude change, the higher the detection accuracy. The most difficult amplitude level to detect was -1mm, with nearly 75% accuracy, while all the other levels had more than 85% accuracy. Moreover, the accuracy for detecting convex amplitudes was higher than for concave amplitudes. Earlier research also showed similar results, that the concave shapes yield significantly higher standard deviations than convex ones in identification tasks [44]. In addition to that, concave amplitudes were easier to detect without visual feedback, possibly because the visual feedback for the sinking movement was limited. In addition, 83% of the participants said that they relied mainly on their sense of touch as opposed to their vision in this concave case.

The results from the second experiment on granularity change showed that the granularity changes in the Pin Array UnCover could be distinguished with an average accuracy rate of 94%; whereas on the Mylar UnCover, the accuracy rate reached 89%. Although the Pin Array UnCover resulted in higher accuracy, probably because the more rigid structure favored tactile perception, involving visual feedback had a greater impact on the improvement of detection accuracy on the Mylar UnCover. This might have been because Mylar is highly reflective and could enhance the contrast of the texture change.

In addition to the performance measurement, post-study questionnaires were also deployed for investigating how the textures could be mapped to different message types. Eighteen message types, such as anger, love, and

laughter, were explained with three labels, Caring and Supportive, Provocative, and Attention-Grabbing. Attention-Grabbing was the message type that participants rated the most appropriate across all prototypes, in particular for the Pin Array UnCover, with the highest amplitude and granularity levels. Caring and Supportive messages were rated most appropriate for the highest magnitudes of shape change for the Pin Array UnCover, whereas on the Mylar UnCover, the lower magnitudes of granularity were more appropriate. Lastly, Provocative messages were associated with granularity changes in both Pin Array and Mylar UnCovers at the highest granularity levels.

Findings from the studies have shown that humans are sensitive in perceiving both amplitude and granularity changes in textures. Moreover, the textures could be implicitly associated with emotional information, which potentially could be used for interpersonal communication. The second version of the UnCovers presented in this chapter also manifested compact mechanisms that could augment current mobile devices with the proposed shape-changing interfaces. Claim 1 was thus confirmed.

Chapter 5

Hand-Gestural Interaction in MSI Applications

Research in Area II aims at answering the second research question: **How can a hand-worn haptic interface be designed for enhancing users' awareness of the surroundings in MSI scenarios?** The studies in Area II target at realizing an envisioned scenario in which users can interact directly by hand with information distributed in the surroundings while maintaining visual attention on the environment. To realize the scenario, we developed the Spatial Sensing Haptic Glove, which features hand orientation and gesture sensing and tactile feedback support.

There are four studies illustrating the iterative development process reported in this thesis. The first study investigated design of tactile guidance cues considering natural hand pointing postures. The second study investigated the feasibility of finding POIs through hand gestural interaction. The envisioned MSI scenario was realized in the third and the fourth studies, in which a glove-based audio-haptic (AH) urban explorer was developed based on the results gained from the first two studies and evaluated in the field. The non-visual urban explorer enabled users to interact with information associated with real-world objects while remaining focused on the environment. While the feasibility of the urban explorer was evaluated in the third study, the possibility of complementing its AH interface with its AR interface (both help users focus directly on the environment) was investigated in the fourth study.

Four publications are included in Area II. The general concept of using the glove as a medium between human and computer for location-aware applications is reported in Publication II. The first three studies are reported in Publication III to manifest the iterative development of the glove and the AH urban explorer. Publication IV reports the third study in detail,

including the design of the urban explorer and the benefits of using such a system in the MSI scenario. The fourth study is reported in Publication V.

The results of the studies showed that participants in the studies considered the tactile feedback and gestural interaction useful and reported that these features helped them focus on the environment when interacting with information distributed in the environment. By comparing the behaviors when using the AH interface and an ordinary touchscreen interface, the studies also showed that participants engaged more with the surroundings through the glove-based interaction. Results from the studies answer RQ2, which could be concluded with the following claims:

- Claim 2** The glove is an effective form factor for enabling mid-air hand-gestural interaction with haptic support in MSI applications.
- Claim 3** Releasing visual attention from the interface and enabling mid-air hand-gestural interaction directly with the surroundings in MSI applications can achieve a higher-level experience of immersion in the environment.

5.1 Design of the Hand-Worn System

This section describes the design and construction of the hand-worn haptic system. I will first describe the envisioned MSI scenario and then the design and development of the research prototype to be deployed in the studies. Fröhlich et al. illustrated a scenario in which direct interaction with the surroundings can be achieved by pointing a mobile device at a real-world landmark [23]. However, this intimate connection with the surroundings diminishes immediately after the user clicks on the selection button because the information presented on the visual interface soon draws the user's attention back to the device; this illustrates a good example of how MSI can help connect users with the real world.

Further expanding from that premise, the system could be improved by deploying a hand-worn sensing device and incorporating an auditory modality to avoid disconnecting from the real environment. In the envisioned MSI scenario, people can locate a POI by following tactile guidance to point directly at a real-world landmark with their hands. By performing clicking or grabbing gestures, they can access the associated geo-referenced content. Moreover, by incorporating the auditory modality to deliver this content, the focus of the visual attention can be maintained on the surroundings, thus avoiding being disconnected from the real environment. Selecting tar-

gets directly with the hand, feeling the touch presented by tactile feedback, and maintaining visual attention on the target builds a sensation of an augmented/extended body that can reach distant and untouchable real-world objects through the glove.

In order to realize the envisioned scenario, the research prototype needs to manifest the following features: accurate hand gestural recognition, tactile guidance, and location-based service. While location-based services can be easily provided by mobile devices, the other two features require more effort to investigate the configuration. The glove form factor was chosen because it affords sufficient space for distributing sensing technologies and actuators, which is also ideal for exploring the configuration of the technologies. To achieve accurate hand gestural recognition, a combination of sensing technologies was deployed on the glove. An inertial measurement unit (IMU) was mounted on the back of the hand for tracking hand pose and orientation, while three flex sensors were deployed on the fingers (thumb, index finger, and middle finger) to detect finger poses. The pointing direction and posture were determined according to IMU readings for yaw, pitch, and roll. The combination of yaw and pitch defines the pointing orientation of the user's hand in a 360-degree, 2D space. To enable MSI applications, the yaw also references magnetic north to calculate the pointing direction with geo-referenced data.

As for the tactile guidance, location is used for encoding directional guidance cues. The main spatial mapping principle deployed is that users move their hands towards the direction where the vibration is perceived, which is generally known as the “pull” metaphor (see Figure 5.4); this method is potentially more intuitive than the opposite “push” metaphor [42]. Following earlier research about deploying tactile guidance on the palm [53], the strategy was to explore actuator placement on the fingers considering the higher density of nerve endings, which supposedly will result in better performance. The first two iterations of the glove (see Figure 5.1 a and b) encompass two sets of actuator setup, one on the fingers and the other on the palm (see Figure 5.2), for evaluating the performance and feasibility of the guidance cue. The experiments confirmed the hypothesis that the finger-based actuator setup results in higher performance. Moreover, when designing pointing-based interactions and considering how we use the hands to interact with everyday objects, vibrotactile feedback can reproduce a more genuine sense of touch on the fingertips than on the palm. In MSI scenarios, where the targets can be distant and untouchable, vibrotactile feedback on the fingertips can enhance the experience by simulating contact with virtual objects [86]. The third iteration of the glove thus has



Figure 5.1: The three versions of the SSH Glove and the system. From left to right are the first, the second, and the third.

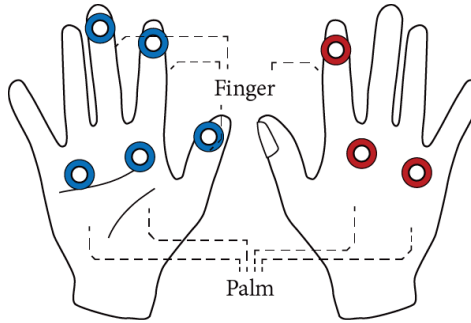


Figure 5.2: The actuator setup of the first glove. The colours depict ventral (blue) and dorsal (red) placements.

only actuators on the fine-tuned locations on the fingers (see Figure 5.1 c). The third version of the glove was deployed in the last two studies, which were the manifestation of practical MSI applications.

In addition to the SSH Glove, the MSI application system also required a mobile device for the location service, auditory interface, system logic, etc. Integrating the glove with a mobile device is a convenient and economic choice since people carry a mobile device with them most of the time, and enabling these additional features on the glove would simply increase its cost and size. The glove communicates with the mobile device through standard Bluetooth, making it versatile for use with a wide range of mobile devices.

The essential feature of interacting directly with a real-world landmark can be achieved by the integration of the above-mentioned technologies. Based on the location information derived from the GPS on the mobile device, the system can understand the user's current location as well as the relative angles between the user and nearby POIs. Meanwhile, the

glove understands in which direction the user is pointing. By comparing the glove orientation and the relative angles to the POIs, the system can understand whether a POI is matched with the user's pointing direction, and the directional guidance can be given accordingly through actuators on the glove. The system can further respond to the user's hand gestures. For example, when the user points at a POI and makes a selection gesture, the system delivers the spoken description of the POI that has been pointed at. Overall, the integrated system realizes direct interaction between the hand and the surroundings without requiring visual attention on the interface.

It is worth mentioning the design of haptic gloves for VR applications since a glove featuring hand-gesture recognition and haptic feedback could be used in both VR and MSI applications. Both application areas would require truthful recognition of hand poses to enable a rich gestural vocabulary, whereas the use of haptic stimuli can have a different focus. The role of haptic stimuli could be twofold - for representing the physicality of untouchable objects (e.g., simulating the sense of touch) and for encoding information (e.g., directional guidance or notification cues). The former may play a more crucial role in VR applications in which the reality is reconstructed through presenting artificial stimuli on our various senses [24]. In this case, haptic stimuli can be a meaningful representation of the physicality of virtual objects touched by the users. More sophisticated examples are gloves using force feedback for grasping in VR [11,28]. Meanwhile, the later may be more relevant to MSI applications since the absence of visual interface could be compensated by a haptic interface. This kind of data gloves has a long history in development. There are also commercialised haptic gloves available on the market, such as Manus glove¹. Hence, pursuing technical novelty is not the main focus of this research. Instead, research in this area focuses on the design of applications adopting matured technologies to explore the design space.

5.2 The Studies

The research question in Area II, "How can a hand-worn haptic interface be designed for enhancing users' awareness of the surroundings in MSI scenarios?" can be translated into the following four sub-questions, which were answered in four separate studies:

1. How should hand-worn sensors and actuators be configured to accommodate users' natural postures while pointing?

¹<https://manus-vr.com>

2. Can hand-worn input and haptic feedback be used to find POIs?
3. What benefits do hand-worn input and haptic feedback have in an MSI application?
4. How can the non-visual audio-haptic urban explorer be complemented by an augmented reality interface to be more versatile?

5.2.1 Study 1 - Tactile Cue Design Considering Natural Pointing Gestures

One of the core features of an urban explorer is to support identifying POIs in an urban environment. At the very beginning of the system development, the aim of the study was to understand how tactile guidance on the hand could effectively support target acquisition tasks. The strategy adopted was to explore the design space and understand how people can naturally point with their hands so that a natural and non-intrusive design of tactile guidance could be derived. Furthermore, the actuator placement for encoding directional guidance was optimized through the comparison with a baseline in the study. The study was designed for answering the first research question “How should hand-worn sensors and actuators be configured to accommodate users’ natural postures while pointing?”

In the controlled laboratory study, the participants were asked to stand at a marked spot in the space surrounded by 16 rectangular targets marked on movable walls. The 16 targets, numbered from 0 to 15, presented 4 azimuth angles (45° , 135° , -45° , and -135°) and 2 inclination angles (7° , and -10° to a reference person), resulting in 8 angle pairs, each with 2 different sizes (see Figure 5.3).

The experiment was divided into two parts. The first part aimed at observing the adjustments in pointing gestures made by the participants due to the glove and the tactile guidance. Participants were asked to point at the targets first without the glove, and then with the glove but without guidance. Since there was no tactile guidance presented, the experimenter read out the number of the target in a randomized order. The design of the experiment provided a chance to observe the most natural pointing gestures and the adjustments made as affected by wearing the glove and learning the cue, which later was taken into account in designing the guidance cue.

The second part aimed at comparing the performance of actuator setups. The same target-acquisition tasks were repeated in this part, in which a within-subjects design of the experiment was followed for examining the performance of guidance on the fingers and the palm. Without receiving verbal instruction of the target number, the participants followed the tactile

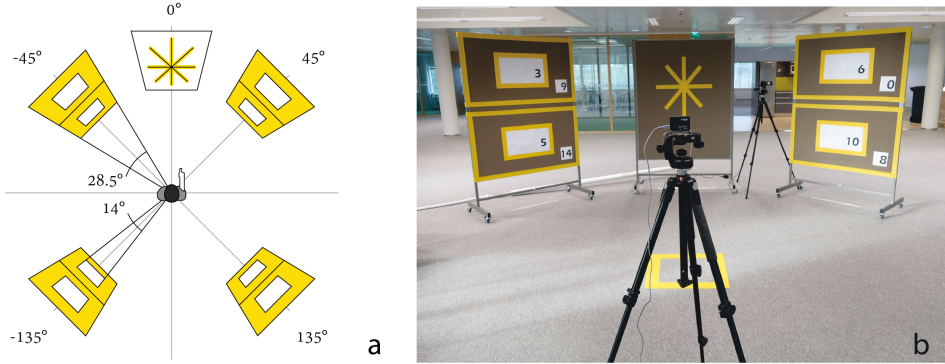


Figure 5.3: The test setup and target arrangement. a) The Schematics b) the experiment environment at -180° (horizontal). The star shape on the middle wall denotes the starting location for the pointing tasks.

cue on the hand to locate the targets. When the pointing orientation fell within the target boundaries, an on-target cue was presented. Meanwhile, the participant could bend the index finger to confirm the selection of the target. The target-acquisition task was repeated for 10 minutes in each condition.

Findings from the experiment helped refine the prototype and the tactile guidance design. The major finding in the first part of the experiment was that horizontal mapping of the tactile guidance can benefit most users since most participants pointed naturally in a horizontal pose. It could also be seen that people who pointed vertically (thumb facing up) would adjust their pointing orientation to align with the guidance pattern that was designed for a horizontal pose. This indicated the importance of aligning tactile guidance with natural hand orientation. The design decision was to adopt a fixed horizontal actuator setup, since there are many aspects that need to be considered if adaptive and customizable guidance cues are to be designed, such as to which degree would the pose be considered horizontal or vertical. Or, would the cue presented on the absolutely horizontal plane regardless of the hand pose (which is achievable on an array of actuators rounding the palm) be a superior option? Thorough investigation is needed for each of these areas. Before fully adaptive customization is possible, the horizontal setup would benefit the most users when designing MSI applications at this stage. The second finding was that tactile guidance on fingertips would be a better setup than on the palm. The results showed that actuators on the fingertips resulted in greater usability, better

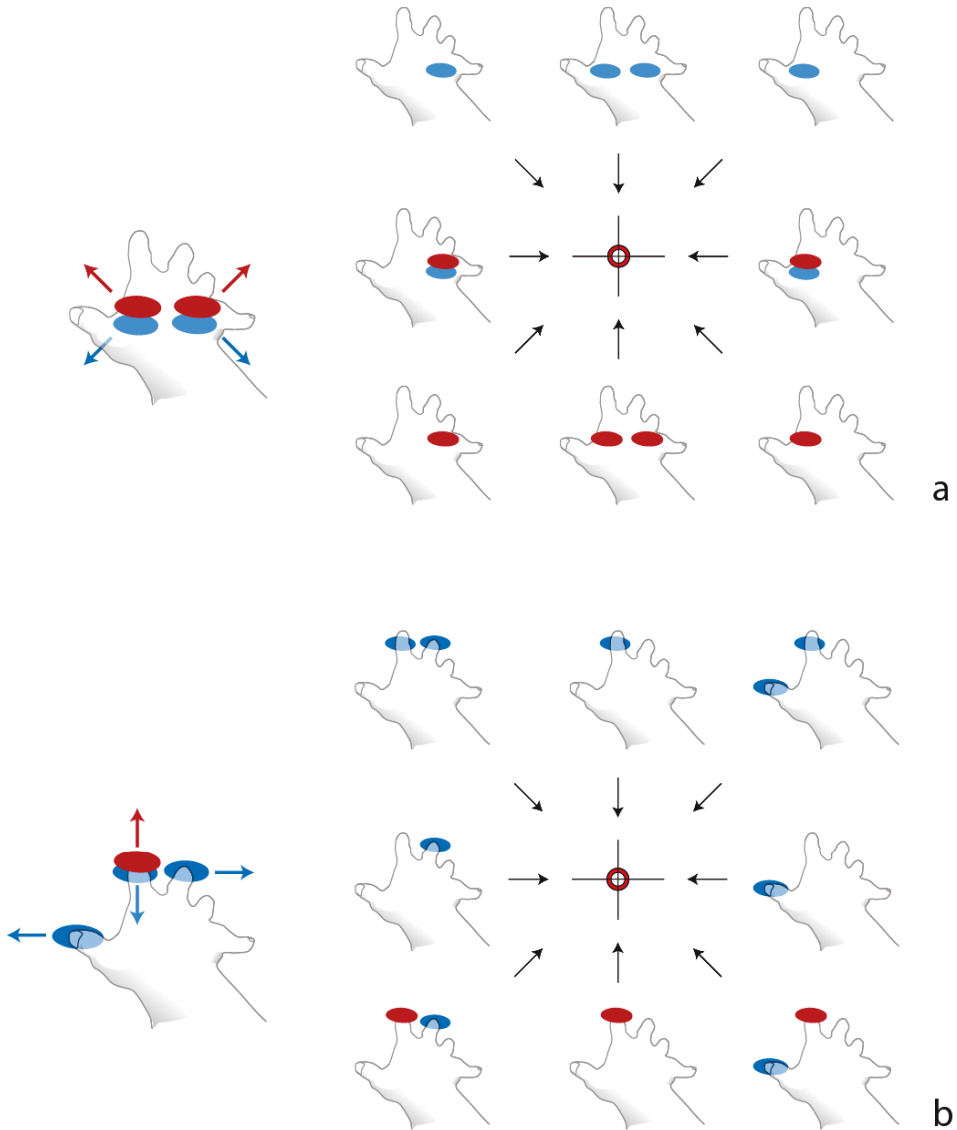


Figure 5.4: Tactile guidance mapping following the color code in Figure ActuatorSetup. Highlighted actuators guide the user to point at the target in the center. a) Guidance mapping for the palm set. b) Guidance mapping for the finger set.

performance, and a lower task load. The finger setup should be further refined in the future.

In terms of prototype design, the glove should be improved by using more flexible fabric, and the appearance should be more robust. It could be observed that simply wearing the glove had an initial impact on the natural pointing pose. People tended to slightly open the palm and also showed concern over damaging the exposed electronics. All these findings encouraged the next iteration of prototype design and a further study shifting from the laboratory to the real environment.

5.2.2 Study 2 - Target Acquisition in Urban Environment

The aim of the second study was to verify whether the tactile guidance could assist users to locate POIs in the real environment. Considering the fact that, in a real urban environment, the landmarks could be very different from artificial targets in a laboratory setting, it is essential to verify the interaction design in a real setting. A preliminary urban explorer application was implemented and integrated with the second version of the glove. The system was deployed in a user study taking place in a central square of the city. The participants were confined to a stationary position before further developing the interaction technique for mobile use. The study was designed to answer the research question “Can hand-worn input and haptic feedback be used to find POIs?”

The urban explorer system incorporated an auditory modality in the interface for delivering content regarding the POIs. Participants wore the glove, headsets, and a mobile device that ran the experimental logic and audio playback. The participants followed the tactile guidance on the fingers because actuator setup on the fingers presented better results in the last experiment. Once the pointing orientation matched the direction of the assigned target, an on-target tactile cue was given along with the spoken title of the POI. After performing a selection gesture (bending the index finger), the participant heard the spoken description of the selected POI. Ten landmarks surrounding the experiment area were chosen as target POIs, which provided good variability in terms of horizontal angle, vertical angle, and angular size (see Figure 5.5).

The results showed that the interaction technique is feasible for locating real-world landmarks. All participants were able to complete the target-acquisition task by following the tactile guidance within a reasonable amount of time and with increasing proficiency. The survey on user experience also showed that 7 out of 12 participants felt quite natural using the glove to directly interact with the landmarks. Even though there



Figure 5.5: The target landmarks presented in a panoramic view. The red rectangles indicate the boundary of each target POI.

was no visual feedback involved in the multimodal interface, the distinctive appearance of the real-world landmarks served well as visual cues. Unlike techniques such as AR or 3D maps, in which users search and look at a replica of the target on the display, using real objects in the surroundings as visual cues could build a direct link between the user and the POI without an intermediate medium.

The development of the glove prototype was much informed by the study. First, the construction of the glove needed to be even more flexible and robust to be able to endure excessive usage in the field. Secondly, the already improved actuator placement for up/down cues on the second version of the glove did not present satisfying results. The two-dimensional spherical cue design unavoidably increased the cognitive load in decoding the information, especially when both visual and audio cues were also presented. Moreover, vibrotactile feedback from the two actuators mounted on the same finger could not be effectively distinguished yet. While more dedicated research is needed for the optimisation of actuator placement for this additional vertical dimension, providing directional guidance in the horizontal plane appeared to be sufficient in this MSI scenario, where the target distribution in the vertical dimension was low. In the next design, the aim was to achieve accurate perception of horizontal directional guidance and designing an MSI application bringing the system to a mobile setting.

5.2.3 Study 3 - Urban Exploration through Audio-Haptic Interface

The aim of this study was to deploy the concept of using the hand to directly interact with the environment into realistic MSI scenarios. The results from previous stationary studies had helped consolidate the fundamentals of the interaction technique for tactile guidance-based target acquisition tasks. The research strategy at this stage was to examine the interaction technique in realistic mobile scenarios. In this study, a location-aware mobile application was developed for urban exploration in which participants

pointed and followed the tactile guidance on the hand to locate surrounding POIs. Participants were able to move around a specific area, receive notifications of nearby POIs, and follow tactile guidance on the hand to locate the target. This study was designed to answer the research question “What benefits do hand-worn input and haptic feedback have in an MSI application?”

Following the system design in the second study, the application incorporated an Android mobile device for running the experiment logic, audio playback and communication with the glove. An additional feature required from the device was GPS service to track participants’ location for providing relevant information while mobile. The third iteration of the glove (see Figure 5.1 (c)), which was more robust and flexible and had a more fine-tuned actuator setup, was deployed in the study. A pair of headsets was connected with the mobile device for delivering audio feedback and spoken information.

The participants followed a predefined path along which 13 POIs were chosen as targets (see Figure 5.6 and 5.7). When entering the radius of a POI, the participant received both audio and tactile feedback indicating the availability of geo-referenced information. By making a selection gesture, i.e., bending the index finger, the participant accepted the recommendation and started following the tactile guidance to locate the POI. When the pointing direction matched the target direction, an on-target vibrotactile cue was given along with spoken name of the POI. Making the selection gesture again initiated the playback of an audio narrative of the POI description.

In order to reveal the benefits of the AH interface, a touchscreen-based application was deployed as a baseline in this between-subject study. Instead of presenting directional information in tactile format, an arrow pointing at the direction of the POI was displayed on the screen. In addition to the performance metrics, the behavior and experience of the participants were collected through video-analysis, questionnaires, and interviews. An additional questionnaire was given to users of the glove, which allowed them to evaluate the audio cues and the experience of using the glove.

The results revealed a major benefit in using the glove-based interface—the reduced division of participants’ attention on the interface and the surroundings. Baseline participants paid much attention to the mobile device instead of the surroundings. Although the description was also delivered through audio once the target was selected, most of the participants still chose to read the text on the screen instead of examining the POI with their eyes. Video analysis showed that they spent an average of 70.27%



Figure 5.6: A map showing the locations of POIs and their associated proximity radius. The red line indicates the predefined route. The two targets in the top right corner were used for training.



Figure 5.7: Participants using the interfaces in the experiment. Left: baseline. Right: the SSH Glove.

($SD = 13.25$) of the time looking at the screen during the exploration of a single POI. Meanwhile, glove participants were able to look at the POI and the surroundings while listening to the description. Other behavioral differences were also observed. While walking, baseline participants tended to constantly check the screen, even though the notification was also accompanied by vibration and required no monitoring of the screen. On the contrary, participants wearing the glove appeared to be simply walking around the city without being distracted by the glove.

In summary, the glove interface enabled using the hand to interact with information associated with the real-world objects, with the benefit of maintaining attention to the surroundings. This is particularly useful when the real-world scene constitutes part of the content that should be paid attention to. By comparing the experience with traditional touchscreen-

based interfaces, the benefits of using the glove-based interface could be immediately manifested.

5.2.4 Study 4 - Complementing Audio-Haptic Urban Explorer with Augmented Reality

The aim of this study is to further examine how the AH urban explorer could be complemented by an AR interface that is also designed to increase situational awareness. The results from previous studies had proven the feasibility of the non-visual AH interface. However, the bandwidth of delivering textual information over audio is limited. Similar to the glove-based interface, sensor-based AR is also based on the point-and-select technique and thus was considered to be integrated on the same system for allowing users to select the more suitable interface to adapt to the dynamic environment. The research aim at this stage was to study the circumstances in which one interface would be preferred over the other, as well as how the interaction of interface switching could be designed. The glove system was enhanced with a sensor-based AR interface and a basic switching mechanism. In the experiment, how the participants chose which interface to use and how they switched the interfaces were studied. This study was designed to answer the research question “How can the non-visual AH urban explorer be complemented by an AR interface to be more versatile?”

The system design was basically the same as in Study 3, except for an additional AR interface implemented on the mobile device. The experiment was conducted in the same area where there are three squares full of tourist attractions. Participants were asked to use the system to explore the squares, first with individual interfaces on the first two squares, then with both interfaces freely on the third square (see Figure 5.8). More specifically, the participants first chose their preferred interface on the third square, and they were allowed to freely switch to the other during the exploration. They were also asked to repeat the last exploration task but with the other interface. This way, the switching of interface was assured to take place at least once and could be studied in case there was no spontaneous switching initiated by the participants.

The participants were asked directly why they chose one interface over another. Accompanied with quantitative measurement, the results indicated that the participants would prefer to use the AR interface when fast access to information was needed or when they wanted to have a view of all the POIs at once. On the other hand, the glove-based interface was preferred when purposeful exploration of a given POI was desired or when

Phase*	Interface			
	AH**	AR**	AR/AH	Map
Uni-Interface phase (on the 1st & 2nd square)	▲	▲		▲
.Task 1: POI identification				
.Task 2: POI picking				
Mult-Interface phase (on the 3rd square)			▲	▲
.Task 1: POI identification				
.Task 2: POI picking with preferred interface				
.Task 2: POI picking with dispreferred interface				

* Each phase was conducted in one square. The order of the squares was counterbalanced

** in a counterbalanced order

Figure 5.8: The tasks and interfaces involved in the mixed design of the experiment. Within-subject factor: interaction mode (AR only v.s. AH only v.s. both AR and AH). Between-subject factor: application (research prototype v.s. Google Maps application).

the participants wanted to listen to the audio rather than read the textual description of the POIs.

The interface switching behavior was studied. The majority of the participants spontaneously switched interfaces during the exploration, indicating that there was a need for a versatile system with multiple interfaces in response to the dynamic environment. This observation corresponds to previous research on users' behavior in urban exploration, where their needs are dynamic and evolving, and it was suggested that the tools should support switching between interfaces [98]. The findings were concluded as recommendations to inform future design (Publication V).

5.3 Findings and Claims

The series of studies manifested the iterative development of the SSH Glove, and the findings concluded Claim 2 and 3 for answering RQ 2. In the earlier stage of development, the glove form factor affords sufficient space for experimenting on tactile guidance design based on actuator placement, as well as distributing sensors for achieving accurate gestural recognition. When deployed in the MSI application studies, the glove could effectively enable participants to interact with the real-world landmarks with the hand, confirming its usefulness in the proposed scenarios.

Moreover, the glove-based AH interface required no visual attention from the users, allowing users to maintain the situational awareness of the

surroundings. As could be seen from the behavioral difference between using the AH and ordinary touchscreen-based interfaces (Publication IV), maintaining visual attention on the surroundings and interacting with information through the hand enabled users to focus on the environment rather than on the interface, hence giving them a more immersed experience.

Chapter 6

Hand-Gestural Interaction with Smart Glasses

Research in Area III aims at answering the third research question: **How can a haptic interaction technique be designed for smart glasses to enable unobtrusive interaction?** Publication VI investigates the issue of social acceptability when using smart glasses in public, reports an in-depth survey of currently available unobtrusive solutions, and develops a set of design principles for designing interaction techniques for smart glasses. The SSH Glove was adopted because it affords independent tracking of the hand and can effectively eliminate attention-grabbing factors. Three use cases of the integrated wearable system are illustrated in Publication VI.

The results of the study showed that participants finished tasks with a positive experience and did not feel especially uncomfortable performing the tasks in public. This answers RQ3; that is, the answer to this question can be framed as:

Claim 4 Independent tracking and accurate recognition of hand gestures can enable unobtrusive and intuitive interaction with smart glasses.

6.1 Design of the System

This section describes the design and construction of the research prototype. As presented in Publication VI, a set of design principles aimed at achieving unobtrusive interaction was derived from the literature review:

1. Isolating sensing technology from the glasses
2. Using relative pointing for adapting to various postures

3. Designing small movements for subtle interaction
4. Aiming for intuitive gestures
5. Enhancing tangibility

The SSH Glove is a feasible interaction technique for smart glasses, mainly because it affords the following features: independent tracking of the hand, accurate hand-gestural recognition, and tactile feedback support. The sensing technologies on the glove are independent from the glasses; hence, the gestures do not need to be performed at eye level, which helps avoid drawing too much attention from bystanders. The sensing technologies can also detect both coarse arm movements and fine-grained finger gestures, accurately reflecting hand gestures and thereby enabling subtle interaction and a wide-ranging gestural vocabulary. Moreover, the glove supports tactile feedback on the action-performing bodies and can contextually enhance the interface's tangibility.

Three interaction scenarios were designed for demonstrating the fundamental 2-D UI on smart glasses: text entry, item selection, and scrolling. In the text entry scenario, a standard QWERTY virtual keyboard was displayed on the smart glasses, as can be seen in Figure 6.1 (a). The keys were grouped in three, and each one was associated with one of the glove's three fingers. By moving their hands, users could select a different key group, whereas by bending their fingers, users could input the key associated with each finger. In the item selection scenario, users could form a pointing gesture, and one of the icons on the interface would be highlighted depending on the pointing orientation, as shown in Figure 6.1 (b). To select the highlighted item, users could simply bend their index finger. To swipe between pages, users could form a grabbing gesture and move the hand horizontally. In the scrolling scenario, the interface presented a long article that was scrollable by performing a grabbing gesture whose inclination determined the direction of scrolling, as shown in Figure 6.1 (c). Interaction design for these scenarios followed the established design principles and demonstrated intuitive hand gestures supported by relevant tactile feedback while maintaining a high degree of freedom.

6.2 The Study

The study is meant to verify the interaction technique's feasibility and social acceptability. Epson Moverio BT-200 smart glasses were used in the study and paired with the SSH Glove through Bluetooth. The handheld

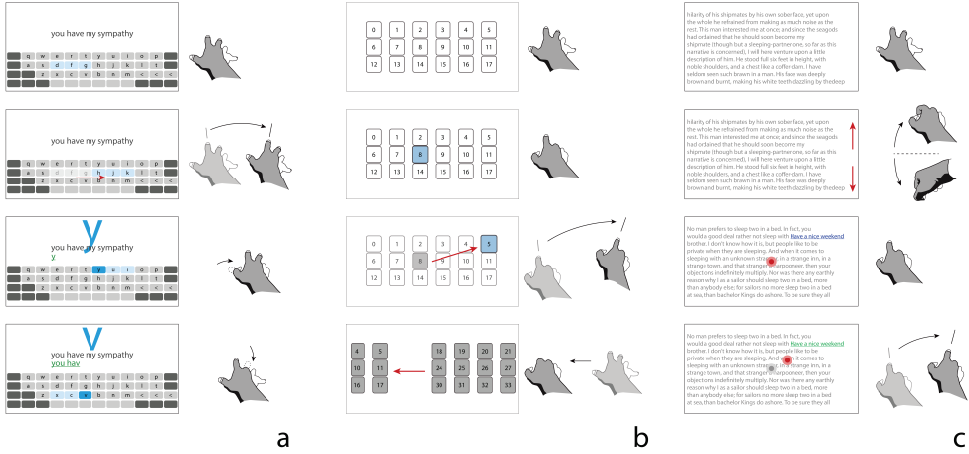


Figure 6.1: The gestures and interface for the three scenarios. a) Text Entry, b) item Selection, c) scrolling.

controller of the smart glasses was not used in the experiment. To obtain more accurate responses regarding social acceptability, participants were asked to perform the assigned tasks in a public area before answering the questionnaires. Each task was explained and demonstrated on a Samsung S5 smartphone, so the interface was visible to both the experimenter and the subject.

Twelve people participated in the quasi-experiment. The three aforementioned scenarios were adopted as tasks in the experiment. Each participant was given the tasks in a counterbalanced order. For the text entry task, participants were given phrases previously selected from the phrase set for evaluating text entry in HCI by MacKenzie and Soukoreff [57]. All subjects were given the same phrase order. When a segment of four phrases was finished, subjects were free to take a break before continuing with the next segment. The entire task lasted for 20 minutes, excluding breaks. For the item selection task, participants were asked to select icons numbered from 0 to 53; these icons were spread over 3 pages (i.e., 18 icons on each page) in a 6x3 grid. All icons were selected one by one in a randomized order. The task was divided into three segments, each for 18 selections. Participants took breaks between segments. For the scrolling task, the interface presented a long article with a hyperlink inserted at random. Participants were asked to scroll through the article to look for the hyperlink. Once the hyperlink was in view, participants could form a pointing gesture to highlight the hyperlink and then select the link by bending their index

finger. The 40 trials were divided into 4 segments. Subjects took breaks between segments.

This study answered the third research question by presenting the design principles gleaned from the literature review, deploying the functioning research prototype in the experiment, and evaluating social acceptability via experimentation in a public area to obtain more accurate responses on participant questionnaires.

6.3 Findings and Claims

To demonstrate how an unobtrusive and intuitive interaction technique can be designed for smart glasses, a set of design principles was proposed, and a functional system was derived for evaluation. The system features independent hand tracking, which allows for interaction from a low position (i.e., not eye level). It also features accurate hand-gestural recognition, enabling intuitive hand gestures included in the gestural vocabulary. Moreover, it supports tactile feedback for enhancing the tangibility of the untouchable visual interface.

The results showed that the glove-based interaction technique achieved satisfying performance compared to previous versions of this technology. Standard words per minute (WPM) is a trustworthy measurement for performance on text entry tasks [2]. The average input speed from our 20-minute experiment was 5.39 WPM ($SD = 1.46$) with a total error rate of 5.45% and 1.14 keystrokes per character. PalmType [102], another hand-worn text entry technique for smart glasses, reached 4.6 WPM on an IR sensor-based prototype. Another study from Grossman et al. [27], done with swiping gestures on a Google Glass frame for text entry, achieved 8.73 WPM for the last segment of an 80-minute experiment. However, error correction was not required in their experiment; thus, a higher error rate, 9.1%, was observed. Our participants exhibited major performance improvements, above all during the first half of the 20-minute experiment. The improvement was also observed for the item selection task, indicating that our participants learned the fundamental interaction quickly.

Independent tracking of the hand and relative pointing enabled participants to freely perform gestures, that is, the participants felt comfortable gesturing. An earlier elicitation experiment on users' preferences for hand postures by Tung et al. [96], in which no real interaction took place, showed that 37% of the gestures were performed in front of the face. However, when evaluated in our functioning interactive system, none of our subjects per-

formed the gestures at this level. Most gestures were performed in front of the lower torso.

In terms of social acceptability, the participants displayed a positive attitude regarding use of the interaction technique in public. Location plays a key role in affecting the willingness to use the glove and smart glasses. The more private (home) or professional (workplace) the location, the more socially appropriate the interaction is. Furthermore, the presence of strangers also limits the hand-gestural interaction. The lowest acceptance rate was found in the presence of strangers for the item selection task, which involved many physical pointing gestures.

The proposed hand-gestural commands were generally considered intuitive by the participants, and the implementation of the tactile feedback was also considered useful, with participants noting that it made the visual interface more “tangible.” Even though there was only vibrotactile feedback presented on the glove, the interaction still required users’ proprioception to coordinate with visual feedback. Overall, a more immersed experience could be achieved through the glove-based haptic interface.

To conclude, the SSH Glove enabled participants to freely determine where to perform the gestures without constraint from the glasses. The findings also showed that most participants decided to perform gestures below eye level to avoid drawing too much attention from bystanders. Claim 4 can thus be derived.

Chapter 7

Conclusion

While motion demands a great deal of visual attention on the environment, interacting with a mobile device demands even more cognitive resources. Both the handheld form factor and the dominant visual interface contribute to the concentration of people's attention on the device's display, which hinders interaction with information when mobile and also causes inattentive blindness. The objective of this research is to provide multimodal interaction to better interact with information while giving proper attention to the environment in mobile scenarios. Exploring hand-based haptic interfaces is the main design approach for developing effective solutions, solutions in which haptic stimuli beyond on-device vibrotactile feedback and mobile hardware solutions beyond handheld form factors were considered.

This thesis has contributed to mobile HCI research through the demonstration of haptic solutions in three research areas: 1) developing expressive haptic stimuli, 2) designing mobile spatial interaction with surroundings as content, 3) interacting with an always-on visual interface. These areas extend along the axis of the explicitness of visual interface, responding to the interface's different levels of visual attention demand. The selected scenarios manifest the most challenging situations facing current interfaces; where haptic solutions may provide the biggest benefit to users. Interaction techniques were designed and prototyped for each scenario and evaluated through empirical studies.

7.1 Summary of the Main Findings

The research questions of the thesis can be answered using the main findings of the studies. The answer to RQ1 can be framed as Claim 1.

Claim 1 Shape-changing interfaces can benefit users by conveying information through static, continuous, and informative haptic stimuli.

Claim 1 was verified through the system prototypes and studies described in Chapter 4. There are two important factors in this claim. First, the haptic stimuli presented through the shape-changing interface should be informative and perceptible. In the two-stage study, participants could distinguish the variations in textures in terms of both granularity and amplitude. Moreover, though implicit, emotional information may be associated with textures, which is germane to interpersonal communication. Secondly, the shape-changing mechanism should be compact enough to be practically installable on mobile devices. As manifested in the second iteration of the prototypes, the two mechanisms required little space and could be practically integrated on mobile devices. The findings indicated that the texture-based shape-changing interface could benefit users by enabling interpersonal communication in mobile devices. Moreover, the textures can be perceived even when the device is inside a pocket, eliminating the need to pull out the device.

The answers to RQ2 can be framed as Claims 2 and 3.

Claim 2 The glove is an effective form factor for enabling mid-air hand-gestural interaction with haptic support in MSI applications.

Claim 3 Releasing visual attention from the interface and enabling mid-air hand-gestural interaction directly with the surroundings in MSI applications can achieve a higher-level experience of immersion in the environment.

Claims 2 and 3 were reached through developing the glove-based hand-gestural interaction technique, as demonstrated in Chapter 5. As opposed to other hand-worn form factors, the glove affords sufficient space for distributing sensors and actuators, enabling accurate hand-gesture recognition, and provides tactile feedback on action-performing bodies. The first study aimed at developing an effective actuator setting for target acquisition tasks. The experiment investigated people's natural pointing postures and the effect of actuator placement on tactile guidance. The findings suggested that tactile guidance be aligned with horizontal posture and that actuators should be placed on the fingers.

Elevated to the application level, the second and the third studies aimed at developing a realistic MSI application in which users can locate nearby

POIs by the hand without the need of visual attention on the interface. In the experiment, the behavior of exploring the city was compared for the glove-based AH interface and a traditional touchscreen interface. Results showed that touchscreen users spent more than 70% of the time interacting with the interface, whereas glove users could look around and pay attention to the surroundings. Given that the proposed interface might suffer from limited information bandwidth, the fourth study investigated how the interface could be complemented by a sensor-based AR interface also designed for increasing situational awareness. Publication V presented an urban exploration system equipped with both interfaces, which enabled users to adapt to the immediate situation by switching to the more suitable interface. The findings were formulated into design recommendations to inform future development. In all, the nonvisual design of the interface was not the only factor contributing to the greater immersion experience, for the glove enabled direct interaction with the surroundings (now the real content) through natural and intuitive gestures, e.g., directly point to, and click on, a landmark, as if the user were interacting with everyday objects. These findings confirmed Claims 2 and 3.

The answers to RQ3 can be framed as Claim 4.

Claim 4 Independent tracking and accurate recognition of hand gestures can enable unobtrusive and intuitive interaction with smart glasses.

Smart glasses seemingly offer a promising solution for enabling head-up interaction while maintaining attention to the surroundings. However, current interaction techniques for smart glasses draw too much attention from bystanders, resulting in user unwillingness to adopt the technology. Chapter 6 demonstrates how the SSH Glove was integrated with the glasses for fundamental interface operations. To enhance the validity of the responses collected from the subjects regarding social acceptance concerns, the study was conducted in a public space. The independent tracking technology on the glove enabled participants to complete the tasks with the hand held in a relatively natural, i.e., low, pose, which proved much less obtrusive than performing hand gestures at eye level. The questionnaire responses also supported this finding: The technique was positively received and viewed as socially acceptable. These findings confirmed Claim 4.

7.2 Implications of the Research

In line with earlier research on mobile HCI, the findings showed that incorporating hand-based haptic interfaces in mobile applications has an immediate benefit in easing the competition of cognitive resources among multiple tasks. However, the findings go further and complement previous research by considering the practical usefulness rather than pursuing compactness. Compactness is commonly conflated with mobility, which has led previous researchers to strive to make the most out of the device. Examples include tactons for presenting high bandwidth in conveying information through vibration [9], “magic wand” techniques for enabling direct interaction with the surroundings [23, 93], and on-frame input techniques for smart glasses [27]. These techniques are compact solutions that require minimal alteration of the original device. However, as discussed here, the concentration of features hinders interaction with information and exacerbates inattentional blindness. In this thesis, compactness was not considered as a constraint to be met, thereby enabling the exploration of wider possibilities in terms of the format of haptic stimuli, form factors, and the incorporation of external apparatus. The practical issues encountered when interacting with information while mobile could thus be confronted.

There are practical implications of this work for interface evaluation and design. Shape-changing interfaces can be implemented on mobile devices, and these interfaces prove beneficial to mobile users in Chapter 4. Even though various use cases of shape-changing interfaces have been explored, they have not been considered both size and power efficient; hence, they are rarely deployed for mobile use. Dimitriadis et al. deployed shape-changing interfaces for mobile device alerts [16]. The amplitude of protrusion-change was as large as 10mm, which resulted in high recognition rate but seemed to require excessive space to integrate into existing mobile devices. In Chapter 4, it has been demonstrated that people were good at perceiving very small changes in shape, indicating that the space and power required in the mechanism would not be as much as expected. This served as the proof of concept. In short, the prototypes and findings in this chapter have important implications for encouraging the design of shape-changing interfaces for mobile use.

The first implication for the design of MSI techniques and applications is the incorporation of a hand-worn, independent tracking device that focuses on mobility and degree of freedom. Mobile conditions are highly dynamic, and users need to adapt to situations quickly and easily. Any constraints on mobility or degree of freedom should be avoided. Chapter 5 demonstrated MSI applications using the SSH Glove with tracking technology indepen-

dent from external devices, ensuring a high degree of freedom. Various form factors of hand-worn devices have been proposed in earlier research, such as a ring [65], or a wrist- or armband [30]. While a ring has a compact size, a wristband leaves the entire hand unoccupied. However, the accuracy of gesture recognition is rather low, resulting in limited gestural vocabulary. The glove form factor, on the contrary, affords sufficient space to distribute sensing technologies for accurate gesture recognition. As a wearable solution, the SSH Glove also allows users to manipulate other physical objects when not in use. Future design could follow this approach to derive haptic solutions with minimal constraints on the hand.

Another implication for the design of MSI applications and interfaces comes in the form of the design recommendation presented in Chapter 5 (Publication V) for developing a multi-interface urban explorer. Again, considering the highly dynamic nature of mobile environments, this thesis explored the possibility of developing a multi-interface urban explorer to enable simple adaption by selecting the more feasible interface for the immediate situation. The findings also showed that participants spontaneously switched interfaces to adapt to the changing environment, indicating the need for such a system. The final recommendations will inform future design.

The research findings in Area III also have important implications for how an interaction technique could encourage or discourage the adoption of new technology. As demonstrated in Chapter 6, drawing too much attention from bystanders when interacting with information could affect people's willingness to adopt a technology, which is consistent with earlier research [81, 96]. Publication VI offers guidelines for the design of an interaction technique for smart glasses that people would be willing to use in public. Moreover, the proposed solution culminated in an integrated wearable system consisting of smart glasses and an independent input device, the SSH Glove. As wearable technologies gradually obtain social acceptance, having multiple input-output devices on the body could enable computers to better understand users' intentions, leading to a more robust and versatile system.

7.3 Limitations

One limitation of the research method used throughout this thesis is to strike a balance between internal validity and external validity. The design of the experiments in this thesis sought to compromise between the pursuit of internal and external validity, thereby entailing studies ranging

from laboratory experiments to quasi-experiments. However, the results' external validity cannot yet be fully addressed without field experiments in natural settings [69]. Moreover, considering the novelty of the interfaces for most participants, the development of habits of use requires a considerable amount of practice and time, which was not included in the studies here.

Incorporating haptic interfaces was meant to ease competition for visual cognitive resources among multiple tasks. However, the interplay between different modalities is complicated. In Area II, the audio modality was also involved in the interaction design. In theory, this kind of time-sharing between sensory modalities is better deployed for cross-modal (auditory-haptic-visual) purposes, rather than intra-modal (visual-visual) ones [105], yet how to achieve balanced resource allocation among different modalities remains an open challenge. Moreover, the cognitive load when processing haptic stimuli needs to be further studied. Although the vibrotactile burst interval-modulated stimuli designed for the glove interface are distinguishable between each other, paying attention to and decoding/processing the stimuli require cognitive resources. Therefore, one cannot naively assume high throughput could be achieved with both visual and haptic channel running in parallel.

Lastly, to develop effective solutions, this thesis investigated selected mobile scenarios. Although the research areas extend from nonvisual to always-on visual interfaces, there are many other scenarios in practice. The results from the research may not be easily generalizable for many of these scenarios.

7.4 Future Research

This work provides a foundation for further development of hand-based haptic interfaces for MSI applications. In light of the fact that content and mobile technologies are evolving at a fast pace, so too should the interaction techniques that bridge the gap between users and information. To further develop methods and solutions, future research should consider each of the research areas included in this study.

Research on Area I could be further extended by considering input methods, for the solution explored textures as information output only. Providing a haptic input method, e.g., pressing, may further complement the haptic interface and enable two-way interpersonal communication. A similar concept has been developed by Pressages [36], where the phone is squeezed to send a vibration to another device in the form of a message.

Continued improvement of the robustness and comfort of the SSH Glove is certainly an important task for the future. Moreover, a long-term study for users to develop their habits of use would provide significant insight into further development of the interface. We observed that participants were still learning how to master the interface and inevitably spent some attention on the interface itself. A long-term study would enable the development of habits and allow researchers to gain insight into how an intimate connection between users and surroundings is forged through interaction design.

The glove-based interaction technique for smart glasses could be further developed to enhance the tangibility of the untouchable visual interface. Similar to the efforts to enhance tangibility in VR applications, future opportunities exist for studying how haptic solutions could enrich interaction with visual contents presented right in front of the eyes. Considering the SSH Glove's advantage in terms of direct tactile feedback on action-performing bodies, further development may potentially help enrich the user experience, e.g., by presenting the attributes or properties of information with tactile feedback.

Finally, the knowledge generated with regard to the effects of incorporating haptic interfaces with MSI applications could be used to optimize cognitive resource sharing. The interplay among different modalities could be further studied. As presented in the last study in Area II (Publication V), the attempt to develop a harmonized multi-interface system was aimed at determining which modalities complement each other. This research did not overlook the strengths of visual interfaces; rather, this research sought to arrive at haptic solutions for circumstances in which visual interfaces appear to be a suboptimal solution. Future opportunities exist for studying how cognitive resource sharing could be arranged for optimizing interface design, thereby achieving easy adaption to the surroundings. This work encourages mobile interaction design to consider haptic stimuli beyond on-device vibration, and mobile hardware solutions beyond the handheld form factor. It also invites designers to consider how to confront the competition of cognitive resources among multiple tasks from an interaction design perspective.

References

- [1] Teemu Tuomas Ahmaniemi and Vuokko Tuulikki Lantz. Augmented Reality Target Finding Based on Tactile Cues. In *Proceedings of the 2009 International Conference on Multimodal Interfaces*, 335-342, ACM. 2009.
- [2] Ahmed Sabbir Arif and Wolfgang Stuerzlinger. Analysis of text entry performance metrics. In *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*, 100-105, IEEE. 2009.
- [3] Amna Asif, Wilko Heuten, and Susanne Boll. Exploring distance encodings with a tactile display to convey turn by turn information in automobiles. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction Extending Boundaries - NordiCHI '10*, 32-41, ACM Press. 2010.
- [4] Gilles Bailly, Jörg Müller, Michael Rohs, Daniel Wigdor, and Sven Kratz. ShoeSense: A New Perspective on Hand Gestures and Wearable Applications. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, 1239-1248, ACM Press. 2012.
- [5] Robert Becklen and Daniel Cervone. Selective looking and the noticing of unexpected events. *Memory & Cognition* 11, 6: 601-608. 1983.
- [6] Hrvoje Benko and Andrew D. Wilson. Multi-point interactions with immersive omnidirectional visualizations in a dome. In *ACM International Conference on Interactive Tabletops and Surfaces - ITS '10*, 19-28, ACM Press. 2010.
- [7] Joanna Bergström-Lehtovirta, Antti Oulasvirta, and Stephen Brewster. The effects of walking speed on target acquisition on a touch-screen interface. *Proceedings of the 13th International Conference on*

- Human Computer Interaction with Mobile Devices - MobileHCI '11*: 143-146. 2011.
- [8] Mark Bilandzic and Marcus Foth. Mobile spatial interaction and mediated social navigation. In *Encyclopedia of Information Science and Technology* (2nd ed.). IGI Global, 2604-2608. 2009.
- [9] Stephen Brewster and Lorna M. Brown. Tactons: structured tactile messages for non-visual information display. In *Proceedings of the Fifth Conference on Australasian User Interface*, 15-23, Australian Computer Society, Inc. 2004.
- [10] Johannes Burge, Ahna R. Girshick, and Martin S. Banks. Visual-Haptic Adaptation Is Determined by Relative Reliability. *Journal of Neuroscience* 30, 22: 7714-7721. 2010.
- [11] Inrak Choi and Sean Follmer. Wolverine: A Wearable Haptic Interface for Grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST '16 Adjunct*, 117-119, ACM Press. 2016.
- [12] Seungmoon Choi and Katherine J. Kuchenbecker. Vibrotactile Display: Perception, Technology, and Applications. *Proceedings of the IEEE* 101, 9: 2093-2104. 2013.
- [13] Roger W. Cholewiak and James C. Craig. Vibrotactile pattern recognition and discrimination at several body sites. *Perception & Psychophysics* 35, 6: 503-514. 1984.
- [14] Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. Surflex: a programmable surface for the design of tangible interfaces. In *Proceeding of the twenty-sixth annual CHI conference extended abstracts on Human factors in computing systems - CHI '08*, 3429-3434, ACM Press. 2008.
- [15] Francis B. Colavita. Human sensory dominance. *Perception & Psychophysics* 16, 2: 409-412. 1974.
- [16] Panteleimon Dimitriadis, Jason Alexander, Panteleimon Dimitriadis, and Jason Alexander. Evaluating the effectiveness of physical shape-change for in-pocket mobile device notifications. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, 2589-2592, ACM Press. 2014.

- [17] David Dobbelsstein, Philipp Henzler, and Enrico Rukzio. Unconstrained Pedestrian Navigation based on Vibro-tactile Feedback around the Wristband of a Smartwatch. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 2439-2445, ACM Press. 2016.
- [18] David Dobbelsstein, Philipp Hock, and Enrico Rukzio. Belt: An Unobtrusive Touch Input Device for Head-worn Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 2135-2138, ACM Press. 2015.
- [19] Marc O. Ernst and Martin S. Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870: 429-433. 2002.
- [20] Jan B. F. Van Erp, Hendrik A. H. C. Van Veen, Chris Jansen, and Trevor Dobbins. Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception* 2, 2: 106-117. 2005.
- [21] Jacques Foottit, Dave Brown, Stefan Marks, and Andy M. Connor. An Intuitive Tangible Game Controller. In *Proceedings of the 2014 Conference on Interactive Entertainment - IE2014*, 1-7, ACM Press. 2014.
- [22] Daryl Fougny and René Marois. Executive working memory load induces inattention blindness. *Psychonomic bulletin & review* 14, 1: 142-7. 2007.
- [23] Peter Fröhlich, Antti Oulasvirta, Matthias Baldauf, and Antti Nurminen. On the move, wirelessly connected to the world. *Communications of the ACM* 54, 1: 132-138. 2011.
- [24] Paulo Gallotti, Alberto Raposo, and Luciano Soares. V-glove: A 3D virtual touch interface. In *Proceedings - 2011 13th Symposium on Virtual Reality, SVR 2011*, 242-251, IEEE. 2011.
- [25] Mayank Goel, Chen Zhao, Ruth Vinisha, and Shwetak N. Patel. Tongue-in-Cheek: Using Wireless Signals to Enable Non-Intrusive and Flexible Facial Gestures Detection. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 255-258, ACM Press. 2015.
- [26] Lada Gorlenko and Roland Merrick. No wires attached: Usability challenges in the connected mobile world. *IBM Systems Journal* 42, 4: 639-651. 2003.

- [27] Tovi Grossman, Xiang Anthony Chen, and George Fitzmaurice. Typing on Glasses: Adapting Text Entry to Smart Eyewear. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '15*, 144-152, ACM Press. 2015.
- [28] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 1991-1995, ACM Press. 2016.
- [29] Shigeru Haga, Ayaka Sano, Yuri Sekine, Hideka Sato, Saki Yamaguchi, and Kosuke Masuda. Effects of using a Smart Phone on Pedestrians' Attention and Walking. *Procedia Manufacturing* 3: 2574-2580. 2015.
- [30] Faizan Haque, Mathieu Nancel, and Daniel Vogel. Myopoint: Pointing and Clicking Using Forearm Mounted Electromyography and Inertial Motion Sensors. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 3653-3656, ACM Press. 2015.
- [31] Chris Harrison and Scott E. Hudson. Texture displays: a passive approach to tactile presentation. In *Proceedings of the 27th international conference on Human factors in computing systems - CHI '09*, 2261-2264, ACM Press. 2009.
- [32] Chris Harrison, Desney Tan, and Dan Morris. Skinput: appropriating the skin as an interactive canvas. *Communications of the ACM* 54, 8: 111-118. 2011.
- [33] Hannah B. Helbig and Marc O. Ernst. Visual-haptic cue weighting is independent of modality-specific attention. *Journal of Vision* 8, 1: 21. 2008.
- [34] Fabian Hemmert, Gesche Joost, André Knörig, and Reto Wettach. Dynamic knobs: shape change as a means of interaction on a mobile phone. In *Proceeding of the twenty-sixth annual CHI conference extended abstracts on Human factors in computing systems - CHI '08*, 2309-2314, ACM Press. 2008.
- [35] Linda A Henkel. Point-and-shoot memories: the influence of taking photos on memory for a museum tour. *Psychological science* 25, 2: 396-402. 2014.

- [36] Eve Hoggan, Craig Stewart, Laura Haverinen, Giulio Jacucci, and Vuokko Lantz. Pressages: Augmenting Phone Calls with Non-Verbal Messages. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology - UIST '12*, 555-562, ACM Press. 2012.
- [37] David Holman and Roel Vertegaal. Organic user interfaces: Designing Computers in Any Way, Shape, or Form. *Communications of the ACM* 51, 6: 48-55. 2008.
- [38] Kasper Hornbæk. Some Whys and Hows of Experiments in Human-Computer Interaction. *Foundations and Trends in Human-Computer Interaction* 5, 4: 299-373. 2011.
- [39] Christopher-Eyk Hrabia, Katrin Wolf, and Mathias Wilhelm. Whole hand modeling using 8 wearable sensors. In *Proceedings of the 4th Augmented Human International Conference on - AH '13*, 21-28, ACM Press. 2013.
- [40] Ira E. Hyman, S. Matthew Boss, Breanne M. Wise, Kira E. McKenzie, and Jenna M. Caggiano. Did you see the unicycling clown? Inattention blindness while walking and talking on a cell phone. *Applied Cognitive Psychology* 24, 5: 597-607. 2010.
- [41] Shoya Ishimaru, Kai Kunze, Koichi Kise, et al. In the blink of an eye - Combining Head Motion and Eye Blink Frequency for Activity Recognition with Google Glass. In *Proceedings of the 5th Augmented Human International Conference on - AH '14*, 1-4, ACM Press. 2014.
- [42] Chris Jansen, Arjen Oving, and Hendrik-jan Van Veen. Vibrotactile movement initiation. In *Proceedings of Eurohaptics*, 110-117. 2004.
- [43] Lei Jing, Zixue Cheng, Yinghui Zhou, Junbo Wang, and Tongjun Huang. Magic Ring: a self-contained gesture input device on finger. In *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia - MUM '13*, 1-4, ACM Press. 2013.
- [44] Astrid M. L. Kappers, Jan J. Koenderink, and Inge Lichtenegger. Haptic identification of curved surfaces. *Perception & Psychophysics* 56, 1: 53-61. 1994.
- [45] Amy K. Karlson, Benjamin B. Bederson, and Jose L. Contreras-Vidal. Understanding one handed use of mobile devices. *Handbook of Research on User Interface Design and Evaluation for Mobile Technology*: 86-101. 2007.

- [46] Idin Karuei, K E MacLean, Z Foley-Fisher, R MacKenzie, Sebastian Koch, and M El-Zohairy. Detecting vibrations across the body in mobile contexts. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 3267-3276, ACM Press. 2011.
- [47] Vinita Khambadkar and Eelke Folmer. GIST: a gestural interface for remote nonvisual spatial perception. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*, 301-310, ACM Press. 2013.
- [48] David Kim, Otmar Hilliges, Shahram Izadi, et al. Digits: freehand 3D interactions anywhere using a wrist-worn gloveless sensor. In *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12*, 167-176, ACM Press. 2012.
- [49] Raymond M. Klein and Raymond M. Attention and visual dominance: A chronometric analysis. *Journal of Experimental Psychology: Human Perception and Performance* 3, 3: 365-378. 1977.
- [50] Marion Koelle, Matthias Kranz, and Andreas Möller. Don't look at me that way! - Understanding User Attitudes Towards Data Glasses Usage. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '15*, 362-372, ACM Press. 2015.
- [51] Barry Kollee, Sven Kratz, and Anthony Dunnigan. Exploring gestural interaction in smart spaces using head mounted devices with ego-centric sensing. In *Proceedings of the 2nd ACM symposium on Spatial user interaction - SUI '14*, 40-49, ACM Press. 2014.
- [52] M R Leek. Adaptive procedures in psychophysical research. *Perception & psychophysics* 63, 8: 1279-92. 2001.
- [53] Ville Lehtinen, Antti Oulasvirta, Antti Salovaara, and Petteri Nurmi. Dynamic Tactile Guidance for Visual Search Tasks. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, 445-452, ACM Press. 2012.
- [54] Mingyu Liu, Mathieu Nancel, and Daniel Vogel. Gunslinger: Subtle Arms-down Mid-air Interaction. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology - UIST '15*, 63-71, ACM Press. 2015.

- [55] Andrés Lucero and Akos Vetek. NotifEye: Using Interactive Glasses to Deal with Notifications while Walking in Public. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology - ACE '14*, 1-10, ACM Press. 2014.
- [56] Arien Mack and Irvin Rock. *Inattentional blindness*. MIT Press. 1998.
- [57] I. Scott MacKenzie and R. William Soukoreff. Phrase sets for evaluating text entry techniques. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems*, 754-755, ACM Press. 2003.
- [58] Karon E. MacLean. Haptic Interaction Design for Everyday Interfaces. *Reviews of Human Factors and Ergonomics* 4, 1: 149-194. 2008.
- [59] Charlotte Magnusson, Kirsten Rasmus-Gröhn, and Delphine Szymczak. Scanning angles for directional pointing. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services - MobileHCI '10*, 399-400, ACM Press. 2010.
- [60] Charlotte Magnusson, Kirsten Rasmus-Gröhn, and Delphine Szymczak. Exploring history: a mobile inclusive virtual tourist guide. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction Fun, Fast, Foundational - NordiCHI '14*, 69-78, ACM Press. 2014.
- [61] Scott D Mainwaring, Ken Anderson, and Michele F Chang. Living for the Global City: Mobile Kits, Urban Interfaces, and Ubicomp. In *Proceedings of The International Conference on Ubiquitous Computing (UbiComp '05)*, 269-286, Springer Berlin Heidelberg. 2005.
- [62] Tiago Martins, Christa Sommerer, Laurent Mignonneau, and Nuno Correia. Gauntlet: A Wearable Interface for Ubiquitous Gaming. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services - MobileHCI '08*, 367-370, ACM Press. 2008.
- [63] Troy McDani, Daniel Villanueva, Sreekar Krishna, Sethuraman Panchanathan, T McDaniel, and Daniel Villanueva. MOVeMENT: A framework for systematically mapping vibrotactile stimulations to fundamental body movements. *2010 IEEE International Symposium on Haptic Audio Visual Environments and Games*: 1-6. 2010.

- [64] Joseph E. McGrath. Methodology matters: Doing research in the behavioral and social sciences. In *Readings in Human-Computer Interaction: Toward the Year 2000* (2nd ed.). Morgan Kaufman, 152-169. 1995.
- [65] David Merrill and Pattie Maes. Augmenting Looking, Pointing and Reaching Gestures to Enhance the Searching and Browsing of Physical Objects. In *Proceedings of the 5th International Conference on Pervasive Computing (Pervasive'07)*, 1-18, Springer-Verlag. 2007.
- [66] S. Misra, L. Cheng, J. Genevie, and M. Yuan. The iPhone Effect: The Quality of In-Person Social Interactions in the Presence of Mobile Devices. *Environment and Behavior* 48, 2: 275-298. 2016.
- [67] Alexander Ng, Stephen A. Brewster, and John H. Williamson. Investigating the effects of encumbrance on one- and two- handed interactions with mobile devices. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, 1981-1990, ACM Press. 2014.
- [68] Tal Oron-Gilad, Joshua L. Downs, Richard D. Gilson, and Peter a. Hancock. Vibrotactile guidance cues for target acquisition. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews* 37, 5: 993-1004. 2007.
- [69] Antti Oulasvirta. Rethinking Experimental Designs for Field Evaluations. *IEEE Pervasive Computing* 11, 4: 60-67. 2012.
- [70] Antti Oulasvirta and Joanna Bergstrom-Lehtovirta. Ease of juggling: Studying the Effects of Manual Multitasking. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 3103-3112, ACM Press. 2011.
- [71] Antti Oulasvirta, Sakari Tamminen, Virpi Roto, and Jaana Kuorelahti. Interaction in 4-second bursts: The Fragmented Nature of Attentional Resources in Mobile HCI. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '05*, 919-928, ACM Press. 2005.
- [72] Taiwoo Park, Jinwon Lee, Inseok Hwang, Chungkuk Yoo, Lama Nachman, and Junehwa Song. E-Gesture: A Collaborative Architecture for Energy-efficient Gesture Recognition with Hand-worn Sensor and Mobile Devices. In *Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems - SenSys '11*, 260-273, ACM Press. 2011.

- [73] J. Pasquero, J. Luk, V. Levesque, Q. Wang, V. Hayward, and K.E. MacLean. Haptically Enabled Handheld Information Display With Distributed Tactile Transducer. *IEEE Transactions on Multimedia* 9, 4: 746-753. 2007.
- [74] Martin Pielot, Wilko Heuten, Stephan Zerhusen, and Susanne Boll. Dude, where's my car?: in-situ evaluation of a tactile car finder. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction Making Sense Through Design - NordiCHI '12*, 166-169, ACM Press. 2012.
- [75] Martin Pielot, Benjamin Poppinga, Wilko Heuten, and Susanne Boll. PocketNavigator: Studying Tactile Navigation Systems In-situ. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '12*, 3131-3139, ACM Press. 2012.
- [76] M I Posner, M J Nissen, and R M Klein. Visual dominance: an information-processing account of its origins and significance. *Psychological review* 83, 2: 157-71. 1976.
- [77] Halley P. Profita, James Clawson, Scott Gilliland, et al. Don't mind me touching my wrist: A Case Study of Interacting with On-Body Technology in Public. In *Proceedings of the 17th annual international symposium on International symposium on wearable computers - ISWC '13*, 89-96, ACM Press. 2013.
- [78] Majken K Rasmussen, Esben W Pedersen, Marianne G Petersen, and Kasper Hornbæk. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems CHI '12*, 735-744, ACM Press. 2012.
- [79] Hanae Rateau, Laurent Grisoni, and Bruno De Araujo. Mimetic interaction spaces: Controlling Distant Displays in Pervasive Environments. In *Proceedings of the 19th international conference on Intelligent User Interfaces - IUI '14*, 89-94, ACM Press. 2014.
- [80] Gang Ren and Eamonn O'Neill. Freehand gestural text entry for interactive TV. In *Proceedings of the 11th european conference on Interactive TV and video - EuroITV '13*, 121-130, ACM Press. 2013.

- [81] Julie Rico and Stephen Brewster. Usable gestures for mobile interfaces: Evaluating Social Acceptability. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*, 887-896, ACM Press. 2010.
- [82] Simon Robinson, Parisa Eslambolchilar, and Matt Jones. Sweep-Shake: Finding Digital Resources in Physical Environments. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '09*, 12:1–12:10, ACM Press. 2009.
- [83] Anne Roudaut, Abhijit Karnik, Markus Löchtfeld, and Sriram Subramanian. Morphees: toward high “shape resolution” in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 593-602, ACM Press. 2013.
- [84] Kathika Roy, Durga Prasad Idiwai, Annapurna Agrawal, and Bani Hazra. Flex sensor based wearable gloves for robotic gripper control. In *Proceedings of the 2015 Conference on Advances In Robotics - AIR '15*, 70:1–70:5, ACM Press. 2015.
- [85] Sonja Rümelin, Enrico Rukzio, and Robert Hardy. NaviRadar: A Novel Tactile Information Display for Pedestrian Navigation. In *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST '11*, 293-302, ACM Press. 2011.
- [86] Robert Scheibe, Mathias Moehring, and Bernd Froehlich. Tactile Feedback at the Finger Tips for Improved Direct Interaction in Immersive Environments. In *VR*, 293-294, IEEE Computer Society. 2007.
- [87] Tobias Schuchert, Sascha Voth, and Judith Baumgarten. Sensing visual attention using an interactive bidirectional HMD. In *Proceedings of the 4th Workshop on Eye Gaze in Intelligent Human Machine Interaction - Gaze-In '12*, 1-3, ACM Press. 2012.
- [88] Marcos Serrano, Barrett M. Ens, and Pourang P. Irani. Exploring the use of hand-to-face input for interacting with head-worn displays. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, 3181-3190, ACM Press. 2014.
- [89] William R. Shadish, Thomas D. Cook, and Donald T. Campbell. *Experimental and quasi-experimental designs for generalized causal inference..* Houghton, Mifflin and Company. 2002.

- [90] D J Simons and C F Chabris. Gorillas in our midst: sustained inattentional blindness for dynamic events. *Perception* 28, 9: 1059-74. 1999.
- [91] Peng Song, Wooi Boon Goh, William Hutama, Chi-Wing Fu, and Xiaopei Liu. A handle bar metaphor for virtual object manipulation with mid-air interaction. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, 1297-1306, ACM Press. 2012.
- [92] Mayuree Srikulwong and Eamonn O'Neill. A comparative study of tactile representation techniques for landmarks on a wearable device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '11*, 2029-2038, ACM Press. 2011.
- [93] Delphine Szymczak, Kirsten Rasmus-Gröhn, Charlotte Magnusson, and Per-Olof Hedvall. A real-world study of an audio-tactile tourist guide. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services - MobileHCI '12*, 335-344, ACM Press. 2012.
- [94] Sakari Tamminen, Antti Oulasvirta, Kalle Toiskallio, and Anu Kankainen. Understanding mobile contexts. *Personal and Ubiquitous Computing* 8, 2: 135-143. 2004.
- [95] Takumi Toyama, Daniel Sonntag, Andreas Dengel, Takahiro Matsuda, Masakazu Iwamura, and Koichi Kise. A mixed reality head-mounted text translation system using eye gaze input. In *Proceedings of the 19th international conference on Intelligent User Interfaces - IUI '14*, 329-334, ACM Press. 2014.
- [96] Ying-Chao Tung, Chun-Yen Hsu, Han-Yu Wang, et al. User-Defined Game Input for Smart Glasses in Public Space. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 3327-3336, ACM Press. 2015.
- [97] Kaisa Väänänen-Vainio-Mattila, Katja Suhonen, Jari Laaksonen, Johan Kildal, and Koray Tahiroğlu. User experience and usage scenarios of audio-tactile interaction with virtual objects in a physical environment. In *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces - DPPI '13*, 67-76, ACM Press. 2013.
- [98] Tuomas Vaittinen and David McGookin. Phases of Urban Tourists' Exploratory Navigation. In *Proceedings of the 2016 ACM Conference*

- on Designing Interactive Systems - DIS '16*, 1111-1122, ACM Press. 2016.
- [99] Daniel Vogel and Ravin Balakrishnan. Distant freehand pointing and clicking on very large, high resolution displays. In *Proceedings of the 18th annual ACM Symposium on User Interface Software and Technology*, 33-42, ACM. 2005.
 - [100] C.R. Wagner, S.J. Lederman, and R.D. Howe. A tactile shape display using RC servomotors. In *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*, 354-355, IEEE Comput. Soc. 2002.
 - [101] Robert Walter, Gilles Bailly, and Jörg Müller. StrikeAPose: Revealing Mid-Air Gestures on Public Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 841-850, ACM Press. 2013.
 - [102] Cheng-Yao Wang, Wei-Chen Chu, Po-Tsung Chiu, Min-Chieh Hsiu, Yih-Harn Chiang, and Mike Y. Chen. PalmType: Using palms as keyboards for smart glasses. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '15*, 153-160, ACM Press. 2015.
 - [103] Side Wei, Gang Ren, and Eamonn O'Neill. Haptic and audio displays for augmented reality tourism applications. In *2014 IEEE Haptics Symposium (HAPTICS)*, 485-488, IEEE. 2014.
 - [104] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 2991-3000, ACM Press. 2015.
 - [105] Christopher D. Wickens. Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science* 3, 2: 159-177. 2002.
 - [106] Daniel Wigdor and Dennis Wixon. *Brave NUI World: Designing Natural User Interfaces for Touch and Gesture*. Morgan Kaufmann Publishers Inc. 2011.
 - [107] Sang Ho Yoon, Ke Huo, Vinh P Nguyen, and Karthik Ramani. TIMMi: Finger-worn Textile Input Device with Multimodal Sensing

- in Mobile Interaction. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, 269-272, ACM. 2015.
- [108] YangLei Zhao, Arpan Chakraborty, Kyung Wha Hong, Shishir Kakaraddi, and Robert St. Amant. Pointing at responsive objects outdoors. In *Proceedings of the 2012 ACM international conference on Intelligent User Interfaces - IUI '12*, 281-284, ACM Press. 2012.
- [109] ISO: Ergonomics of Human-Computer Interaction - Part 910: Framework for Tactile and Haptic Interaction. 2009.

